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3D MODELLING OF A 15TH CENTURY CITY GATE OF RENNES: PORTES MORDELAISES

MODELADO EN 3D DE UNA PUERTA DE LA CIUDAD DE RENNES DEL SIGLO XV: PORTES MORDELAISES

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Highlights:

- The Portes Mordelaises, a 15th century defensive gate and associated structures, one of the principal historical sites situated in Rennes, France, has been entirely virtually reconstructed in 3D.
- An original methodology was adopted in order to reconstruct the 3D model of this unique architectural edifice over the course of its six-year excavation.
- Recognised as being of great national interest, a virtual reality installation was created in an exhibition presenting its reconstruction, garnering more than 45000 visitors.

Abstract:

The Portes Mordelaises, remnants of the medieval city walls of Rennes, France, has been the subject of several archaeological excavations until 2017. From these excavations, we created a three-dimensional (3D) model of the site reconstructed as it would have appeared during the 15th century, including the surrounding plus the interiors of its famed towers. Once our efforts and results were officially recognised as being of national interest by the French Ministry of Culture and Communication, Department of Heritage and the National Museum Service of France, we presented our virtual model reconstruction in an exhibition curated by the Museum of Bretagne, entitled "*Rennes, les vies d'une ville*" (Rennes, the Lives of a City). This approach to 3D reconstruction of the site served to further study Rennes' origins, its construction, organisation, as well as its historic relationship to surrounding territories. The main objective of this work was to investigate, using of a significant and complex archaeological site as proof of concept, how the digitalisation of an existing structure, the modelling of its hypothetical structures, and the interactions with its virtual spaces enabled the general public to provide critical feedback, and enhance archaeological knowledge and evaluation of such sites. This reconstruction was carried out under a West Digital Conservatory of Archaeological Heritage project, whose mission is to support and advise archaeologists in the production and exploration of 3D archaeological datasets using the latest digitisation, modelling, and virtual reality (VR) techniques. Through a complex but repeatable process, using the valuable data provided by various excavations, in addition to new information provided by the 3D digitalisation itself, we produced a 3D model, fully satisfactory to rigorous scientific standards, which was then incorporated into a VR space ready for diffusion to the general public. Furthermore, the fact that 45850 visitors were welcome to experience our 3D model at an exhibition in a city the size of Rennes proved to be a significant success.

Keywords: 3D modelling; medieval walls; barbican; virtual archaeology; public exhibition; virtual reality (VR)

Resumen:

Las *Portes Mordelaises*, restos de las murallas medievales de la ciudad de Rennes, Francia, han sido objeto de varias excavaciones arqueológicas hasta el año 2017. A partir de estas excavaciones, pudimos crear un modelo tridimensional (3D) del sitio reconstruido tal y como habría aparecido durante el siglo XV, incluyendo los terrenos circundantes así como los interiores de sus famosas torres. Una vez que nuestros esfuerzos y resultados fueron reconocidos oficialmente como de interés nacional por el Ministerio de Cultura y Comunicación de Francia, el Departamento de Patrimonio así como el Servicio Nacional de Museos de Francia, presentamos nuestra reconstrucción del modelo virtual en una exposición gestionada por el Museo de Bretaña titulada "Rennes, las vidas de una ciudad". Este enfoque de la reconstrucción en 3D del sitio sirvió para profundizar en el estudio de los orígenes de Rennes, su construcción, su organización, así como su relación histórica con los territorios circundantes. El objetivo mayor de este trabajo fue investigar, mediante el uso de un sitio arqueológico significativo y complejo como prueba de concepto, cómo la digitalización de una estructura existente, el modelado de sus estructuras hipotéticas, y mediante interacciones con sus

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espacios virtuales donde el público en general podría proporcionar una retroalimentación crítica, y mejorar aún más el conocimiento arqueológico y la evaluación de dichos sitios. Esta reconstrucción se llevó a cabo en el marco de un proyecto del Conservatorio Digital del Patrimonio Arqueológico de Occidente, cuya misión es apoyar y asesorar a los arqueólogos en la producción y exploración de conjuntos de datos arqueológicos en 3D utilizando las últimas técnicas de digitalización, modelización y realidad virtual (RV). Gracias a un proceso intrincado y arduo, pero repetible, que utiliza la gran riqueza de datos proporcionados por diversas excavaciones, además de la nueva información aportada por la propia digitalización en 3D, pudimos producir un modelo en 3D plenamente satisfactorio con arreglo a normas científicas rigurosas, que luego se incorporó a un espacio de RV listo para su difusión al público en general. Además, para nuestro equipo, el hecho de poder acoger a 45850 visitantes para experimentar nuestro modelo 3D en una exposición en una ciudad del tamaño de Rennes resultó ser un verdadero éxito.

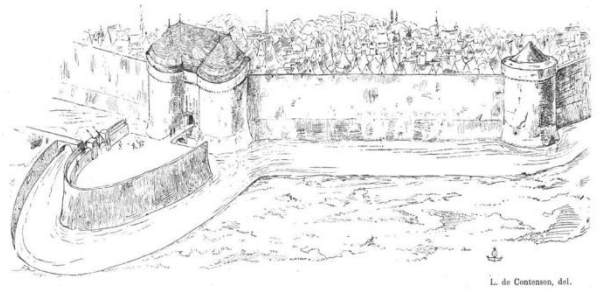
Palablas clave: modelado 3D; murallas medievales; barbacana; arqueología virtual; exposición pública; realidad virtual (RV)

1. Introduction

1.1. Historical context

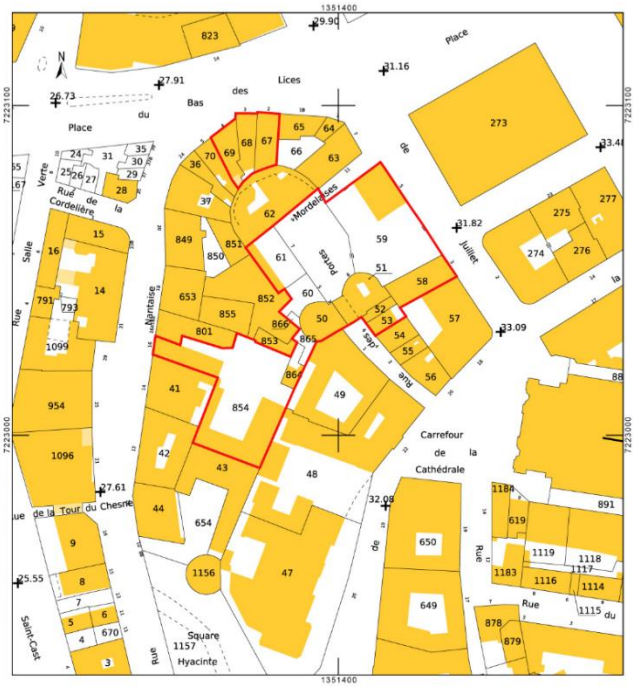
First established 2000 years ago at the confluence of the Ille and Vilaine rivers under the name Condate, prior to being renamed *Civitas Riedonum* during the Late Roman Empire, Renne has been fitted with defensive walls since the end of the 3rd century. Rigorously studied for more than a century now (Contenson, 1907) (Fig. 1a), the ancient fortification was frequently maintained and repaired until the 15th century, at which point the city ascended greatly in influence and became the coronation site of the dukes. It was during this period that John V, Duke of Brittany, had constructed a new enclosing wall to protect the newer city establishments to the east. Parallel to this, the walls of the ancient city, most particularly the Portes Mordelaises (Fig. 1b) situated along the road leading to the original wall, was undergoing intensive reconstruction: restored in 1418 to serve as the residence of the city's governors, and then partially rebuilt between 1442 and 1452. Between 1449 and 1476, the fortification of the city expanded even further with the construction of a third enclosing wall encompassing the rest of the newer city, including in particular the districts built south of the Vilaine housing the Carmelite convent.

Starting in 1464, in an effort to bolster the security of the existing fortifications, several advanced structures were built in front of the gates to form a walkway for artillery units, as well as a semi-circular barbican with three levels of casemates bearing cannon-embrasures. However, the new fortifications were quickly decommissioned. As early as 1602, Henri IV ordered the towers and gates to be dismantled. The Portes Mordelaises, inhabited by a captain, was spared such a fate. From 1636, Louis XIII authorized the sale of channels, bastions and ramparts surrounding the wall. The moat-trench between the Portes Mordelaises and the Duchesne Tower, sold to private individuals in 1694, was quickly urbanized and integrated into a vision closer to modern Rennes.



(a)

(b)



(c)

Figure 1: a) Oblique view drawn at the beginning of the 20th century (Contenson, 1907); b) The Mordelaises Gates at present day; c) Excavation permitted regions (Esnault, 2012).

1.2. Archaeological excavations

On the 11th of June 1926, the site of Portes Mordelaises was included in the supplementary inventory of the French historic monuments, becoming officially the property of the city of Rennes in 1970. As of present, this emblematic remembrance of the fortifications of Rennes is currently the subject of an ongoing development project. An archaeological study was commissioned by the city of Rennes: it was planned as a multi-year affair which included the entranceway, the barbican and the two sections of curtain wall on either side of the gates (Fig. 1c). The first surveys of the remains of the ancient wall were carried out in the 19th century during an urban planning campaign to canalise the Vilaine, which greatly advanced the dismantling of the medieval fortifications.

In 2012, the first excavation began exploring the earthwork of the embankments which had been filled in up to the curtain wall of the structure, followed by the north tower and the barbican (Fig. 2a). The survey revealed the anteriority of the medieval curtain wall in contrast to the north tower, thus indicating a renovation of the fortification occurring before the construction of the 15th century wall. These improvements are likely associated with the various sieges suffered by the city between the 9th and 14th centuries. Following the extraction of contemporary embankments, most likely additions dating to the urban planning project in the 19th century, the remains of lightweight structural materials were revealed (Esnault, 2013), expressing a rapid settlement of trenches in the 17th century.

The work in 2013 focused on the further excavation of the trenches and a specific study of the entrance gate, the adjacent curtains and the artillery walkway. Initial reconstruction of the ancient fortifications in the early Middle Ages has been documented. Part of the eastern curtain wall was built at that time by reusing antique materials from earlier iterations. The second phase of significant construction saw the erection of a building of distinctive status integrated into the west curtain wall during the last third of the 13th century. This wall included three gemel windows. Located in the immediate vicinity of the cathedral, an episcopal palace was visible from the wall. The entrance, which was built either at the end of the 14th-century or the beginning of the 15th century, was accompanied on the interior city-side of the wall by an unknown building which has today disappeared but whose vertical displacement of persons was evident during the surveying of the site. Originally vaulted, the ground floor and upper level of the towers had undergone a major restructuring in the early modern period, which required the demolition of said vaults in order to introduce additional levels. This period of construction affirms the decommissioning of the Portes Mordelaises, formerly known as the Royal Gate, through which the Duke used to access the city (Esnault, 2014b).

The third excavation phase scheduled for the Portes Mordelaises focused more specifically on the artillery walkway. The study showed that the archaeological levels were perfectly preserved despite numerous subsequent alterations, including the installation of buildings during the early modern period and their eventual demolitions at the end of the 20th century. Seven manual excavations conducted in the former building's cellars identified the boulevard's central reserve with its levels of pathways formed by gravel (15th-17th centuries). The hypothesis of two phases of construction for the advanced structure were tested and verified: a first barbican, far smaller in comparison, was extended and transformed into a genuine walkway for artillery units during the 15th century. While the knowledge of its original state is currently missing, the second state is now well documented and its architectural organisation has been concluded. Thanks to the positionalities of the arrowslits, the extreme limits of the trenches were reinterpreted far more precisely than before.

The main point of curiosity was the richness and complexity of the stratigraphy, which has been very well-preserved despite numerous subsequent reorganisations of the surrounding plots. The excavation of the artillery walkway (Fig. 2b) provided the discoveries of various antiquities (metal coins and ceramics), which make it more readily possible to determine the initial fluxes of occupation starting from the end of Antiquity to the Early Middle Ages, further renewing the excavation's principle concerns. This raised the question of the possible presence, dating back to Antiquity, of a door in the wall associated with a prominent axis. The entrance would thus have made it possible to fix portions of the ancient urban structure (Esnault, 2015a).

In 2015, the levels of construction relating to the walkway were finished and documented. But it was, above all the rest, the discovery of earlier remnants which were of particular interest. First of all, a moat built during the Late Roman Empire or Late Antiquity was revealed (Fig. 2c). It was connected to the curtain wall. After having suffered great damage during a violent fire, the moat was restored and remained in operation during the early Middle Ages. It was during this period that the defensive capabilities of the wall were doubled by the installation of a second moat as well as the construction of a crossing between the two. The presence of large posts intersecting in the trench also materialized, suggesting the presence of an ancient axis stemming from the decumanus path leading toward the Cathedral of Rennes to the north. The Portes Mordelaises, therefore, would seem to likely be a replacement for an older gate built alongside the construction of the curtain wall during the Late Roman Empire. It was not until the 13th century that the entrance to the city was completely restructured: the ancient axis was definitively abandoned and diverted, as the moats were filled in and the curtain wall rebuilt after it had been levelled. The archaeological layers of this period have produced many significant ancient finds such as tiles (imbrex and tegulae), bricks, small shale waste and many oyster shells. The western curtain wall had been rebuilt sometime between 1260 and 1290 by integrating a prebendal manor. These building efforts, aimed at modifying the entrance to the city and restructuring the areas directly behind the curtain wall, are concurrent with the reconstruction of the Cathedral between the 12th and 14th centuries and were certainly carried out at the instigation of John II (1286-1304), who was responsible for the restoration of many castles and urban enclosures. However, the development of the city entrance was not yet complete. Staring in the 14th century, we witness the construction of far greater defence capabilities. Access from the entrance to the city was therefore diverted. The

walkway for artillery, as we see it today, is probably only a redevelopment of an earlier design, transformed gradually to adapt to new artillery and needs. In any case, it is certain that the Portes Mordelaises was already equipped with an advanced defence structure in place when, in 1464, Rennes equipped all its gates with walkways for artillery. The first "*compte des miseurs*" (accountant) in 1418 already suggested the presence of an advanced structure for defence. Attested by the 2015 excavation, it has allowed ageing a part of the wings and walls by about a hundred years. The organisation of the architecture of its first construction was documented by the discovery of a staircase, which appeared to have been abandoned in the 15th century due to damage caused by a violent fire. We can imagine that the construction of this first advanced structure is due to the initiative of John IV the Conqueror, who rose from 1382 a "*devoir de clouaison*" (duke established taxes) for the restoration of urban defence structures (Esnault, 2016b).

(a) (b) (c)

Figure 2: General views of the excavation: a) From the ground; b) From the top of the gate (Esnault, 2012)(Esnault, 2012); c) Ancient reddened trench (Esnault, 2015a).

1.3. Context of 3D reproductions

Defensive structures are regularly digitized and/or modelled (Athanasoulis et al., 2015; Canciani, Conigliaro, Grasso, Papalini, & Saccone, 2016). More particularly, a great number of famous city gates have been reconstituted in 3D, such as the Holstentor (Lübeck, Northern Germany) (Jahn, Kersten, & Kinzel, 2004), the Powder Tower (Prague, Czech Republic) (Ferko et al., 2004), the Porta Nigra (Trier, Germany) (Boochs, Hoffmann, Huxhagen, & Welter, 2006) or more recently the Ishtar Gate (Pergamon Museum, Berlin, Germany) (Al-Baghdadi, 2017).

As for French historic structures, the 3D Warehouse[1] (Fisher & Hanrahan, 2010) has a number of gates already included. Much like our subject of study, some of which were similarly equipped with towers. These include the Porte des Allemands (Metz), Porte Horloge (Vire), Porte Saint-Pierre (Nantes), Porte des Cordeliers (Falaise), Porte Rivotte (Besançon), and four gates in Carcassonne: Porte Narbonnaise, Porte de Rodez, Porte Saint Nazaire and Porte de l'Aude. However, these 3D models were only produced by traditional digitisation techniques. At the same time, it should be noted that an important modelling work has been carried out for the 3D restitution of the Porte Cailhau (Bordeaux) as it would have been during the 17th century (Châtellier, 2011). More recently, there have been 3D reconstructions of the supposed states of the Bannier Gate, the main entrance to the city of Orléans in the 14th and 15th centuries (Alix, Carron, Roux-Capron, & Josserand, 2016). Few barbicans have been digitized or reconstructed. We can still cite the Kraków Barbican (Ozimek, 2007; Marek & Hipp, 2011), a piece of tapial wall of the Province of Seville (Barrera-Vera, 2005), as well as the circular structures encircling Beijing (Zhangyu, 2014). The reconstruction of the Bannier Gate also presented a proposal for a barbican (Alix et al., 2016). Various 3D production projects about Rennes, in general, have been carried out (Regnard, 2015).

[1] https://3dwarehouse.sketchup.com

They focus on the existing, or certain recent histories, though the details have not systematically been the subject of historical or archaeological research and verification. Restitution of the Portes Mordelaises was also carried out, but before the excavations began, and is therefore not scientifically relevant to our goals (Ouest-France, 2013).

In the north-west of France, the West Digital Conservatory of Archaeological Heritage (WDCAH) project is a research organisation whose aim is to both ensure the preservation of digital archaeological data, as well as to deliver expertise in production, analysis, visualisation and VR exploration techniques (Barreau, Gaugne, Bernard, Le Cloirec, & Gourantoet, 2013). In 2013 the WDCAH began an iterative process of 3D modelling during excavations. At that time, the WDCAH oriented its 3D productions towards research approaches in the development of VR tools for archaeologists. The 3D restoration process has since moved further in this direction. Given the start dates of our project, even if WDCAH's contributions held great importance, the archaeological and historical data concerning the exterior of the building, in particular, did not seem to be diverse enough to be integrated into a Building Information Modelling (BIM) process at the time. BIM tools are, however, broadly used for architectural heritage in France and throughout Europe (Banfi, Brumana, & Stanga, 2019), museums (Tucci et al., 2019), and can also be oriented with VR applications in mind (Brioso, Calderón, Aguilar, & Pando, 2019; Pybus, Graham, Doherty, Arellano, & Fai, 2019).

2. Method

Although not initially defined as such, five distinct sections of the Portes Mordelaises stood out during the 3D reconstruction process. The work on these portions was carried out independently according to archaeological discoveries and reasoning. These are as follows: the entrance and its two towers, the walkway for artillery and its surroundings, the stables set up for the governor, the curtain walls and plots directly behind the Gates.

2.1. Entrance

2.1.1. The exterior

Before the actual restitution process began, two digitisation procedures closely linked to the excavation were carried out. Even if they were not initially intended to be part of the 3D modelling process, they were still used to support the overall outcome. Splines corresponding to the external dimensions were thus used for geometric modelling. Photogrammetry made it possible to orient the textures mapped to the dimensions of the towers.

A tacheometer survey, done with a Leica TCR 407 (Mora & Vivier, 2007), allowed us to create 3D splines of both the interiors as well as the exteriors of the entrance (Fig. 3a). In concrete terms, these splines were generated from the surveyed topographic points corresponding to the currently existing structure. They were not given any further treatments seeing as how the missing elements and differences with the supposed state of the building in the 15th century were of potential importance.

Following the example of the previous digitisation operations mentioned above, photogrammetry was also performed mounted on a boom (Guillas, 2013). In 2013, the 120 photos we obtained made it possible to render a 3D mesh with 751600 faces and 423400 vertices using Agisoft PhotoScan v. 0.9.1 (Fig. 3b). The purpose of this photogrammetry was to provide a first 3D visual documentation for excavation reports.

From these first 3D details, we started to model in particular the external walls of the entrance (Fig. 3a). We could have used the photogrammetric model (Remondino, 2003), but the proportion of hypothetical parts to existing parts was initially uncertain and revised frequently during the excavations. As the existing measures were relatively simple, we decided to model them in a traditional way and we believe that the time allocated for these components was in a way excessive. In order to ensure an efficient exchange between the archaeologist and the graphic designer, we used toon-shading (Fig. 3b) to prevent any graphical misunderstandings. This technique is used in archaeology (López, Arroyo, & Martín, 2012) and has become quite important, not only in game-design but in architecture as well, since several years (Freudenberg, Masuch, Rober, & Strothotte, 2001; Haller, 2004). In our case, this eliminated a number of ambiguities about dimensions and distances.

The texturing of the towers has been the subject of particular work. The quality of the textures generated with photogrammetry was not good enough to be used on a model that has to be seen up close. With Photoshop CC 2017 18.0 and from various photos, we chose to build orthophotos of the unfolded towers. These close-up photos, taken at different dates, were very heterogeneous and did not allow for photogrammetry. But by cutting out certain parts of them, and homogenizing their colours with the Photoshop's Match Color tool, we obtained a result whose resolution was satisfactory. Their mapping was then completed using the UVW Map Modifier of 3DS Max 2017 on a cylindrical map (Fig. 4).

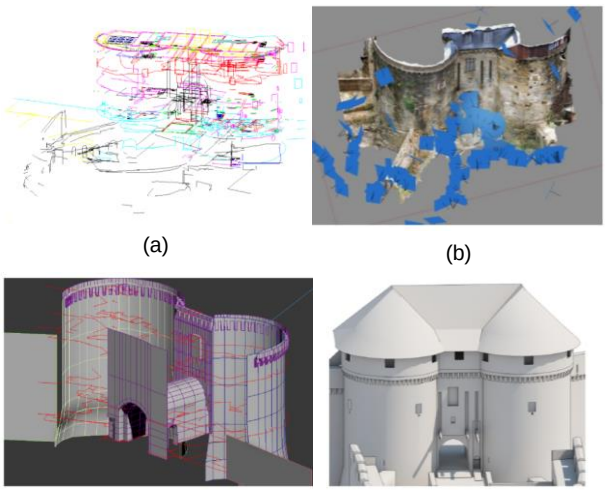


Figure 3: a) 3D splines from a tacheometer survey; b) Photogrammetry of the existing gates (Guillas, 2013); c) Modelling from splines; d) Working document (Esnault, 2016a) presenting a modelling step in the entrance modelling process and rendered with VRayToon (Bayraktar, 2016).

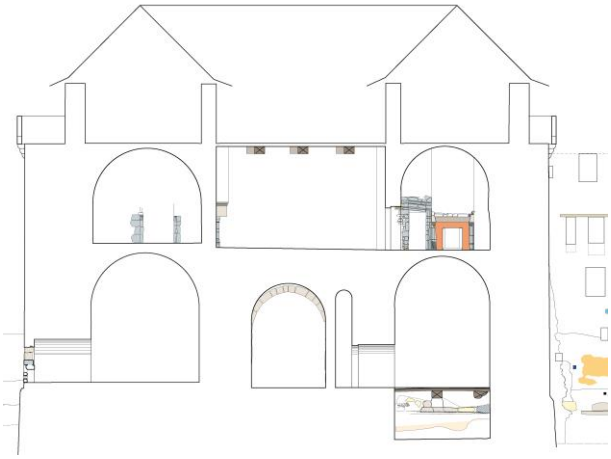
Figure 4: Orthophoto of the unfolded East Tower.

2.2. Underneath and inside

It is the cart drivers passageway that gives access to the interiors of the towers (Fig. 5a). In the east tower, there are currently posts that support the wooden staircase and the scaffolding on the left (Fig. 5b). In the other tower, the governor's room on the 2nd floor has a fireplace with medieval characteristics (granite, shale and limestone) (Esnault, 2014a).

2D documents concerning the interior have been produced previously (Fig. 5b), notably for consolidation, flood-proofing operation and diagnosis (Esnault, 2014a). The evolution of the interior having been so essential to understanding its development over time, that the reconstruction of the dimensions corresponding to the 15th century was also mainly based on the archaeological hypotheses.

(a)

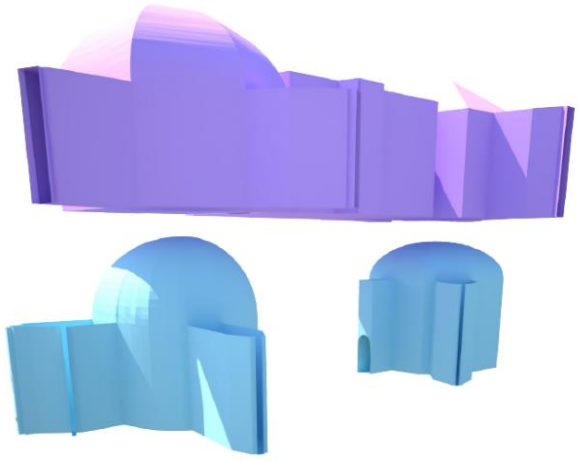


(b)

Figure 5: a) Photos; b) 2D document allowing the modelling of the interior and the passage under the Gates (Esnault, 2014a).

The dimensions of the cart drivers passageway have been surveyed with both the tacheometer and photogrammetry surveys mentioned above. There was so no particular difficulty in its 3D recreation, though creating a texture for the passage proved more difficult. Orthophotos were made with photogrammetry but they needed to be completed using a combination of photographs and Photoshop's Clone Stamp Tool (Fig. 6a) (Barreau, Lanoe, & Gaugne, 2020). The texture mapping went smoothly as the top of the passageway corresponded to a nearly perfect half-cylinder. The greatest challenge in modelling the interior's walls (Fig. 6b) was having a clear understanding of the architectural style being applied to the hypothetical vaulted ceilings, as they too related to the contours of the rooms. The global section (Fig. 5b) was used as a principal source, but there were indeed variations in the 15th century concerning the levels of the West Tower. The archaeologist consequently provided new sections annotated with altimetry deduced from further study of the walls. The vaulted ceilings could be properly modelled by drawing out divisions of circular splines from the corners of the rooms to their corresponding keystones.

(a)



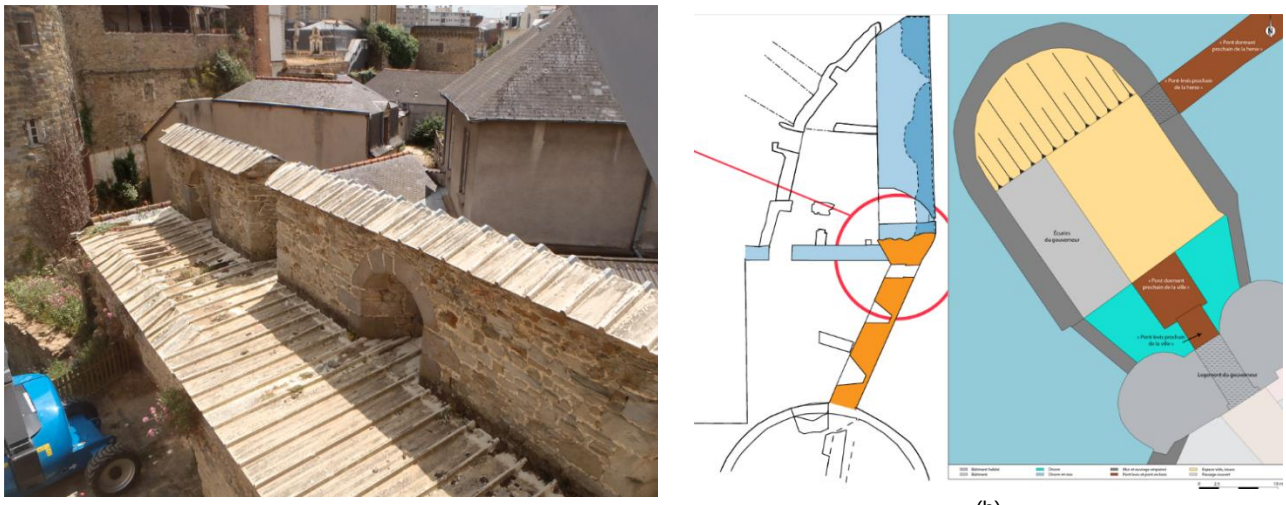
(b)

Figure 6: a) Orthophotos of the passage; b) Modelled indoor volumes.

2.3. Artillery Walkway

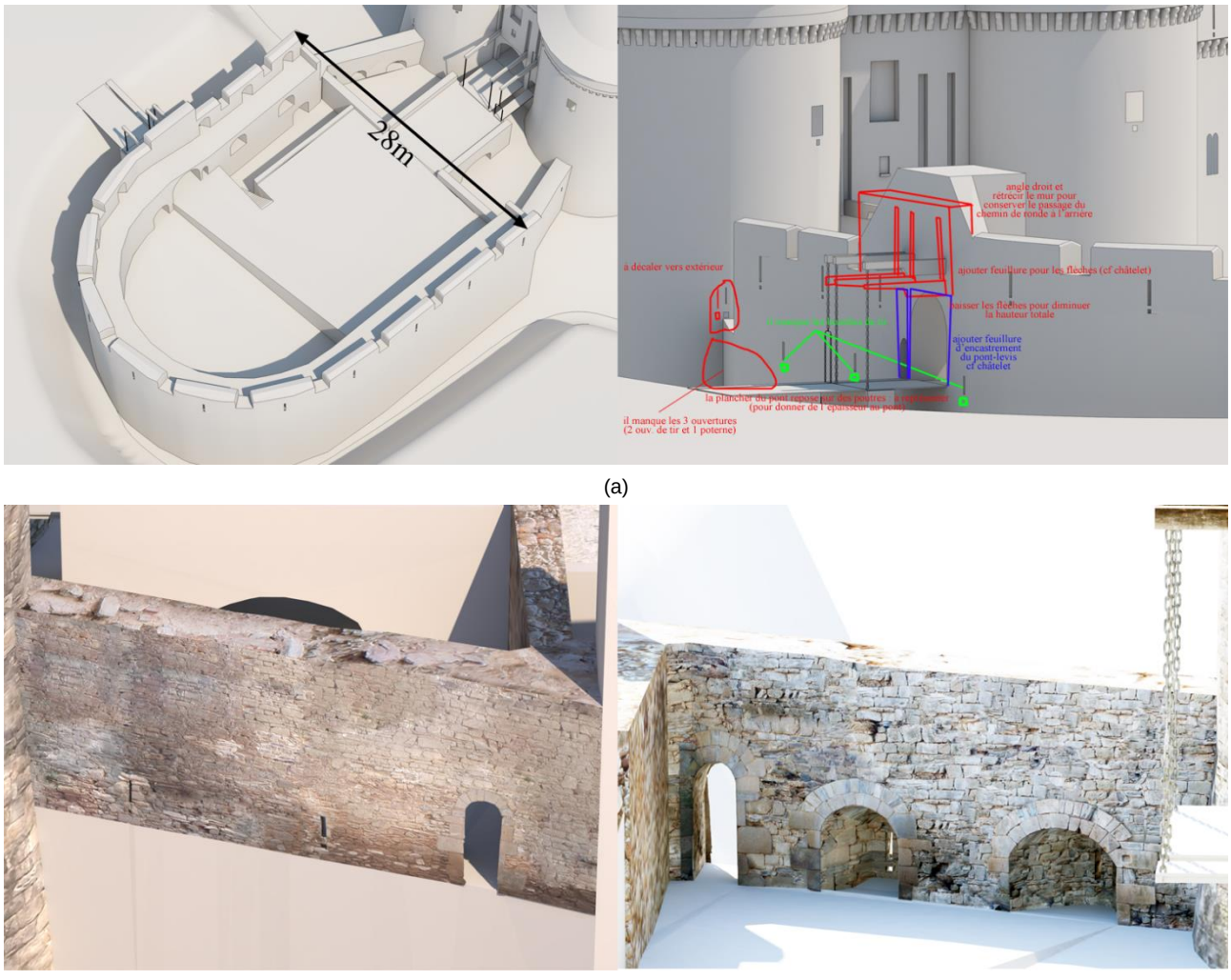
Like the entranceway, the modelling of the artillery walkway was based on the 3D splines from the tacheometer survey. Documentation (Fig. 7b) and photographs (Fig. 7a) made it possible to reproduce the hypothetical elements and texture them, in the same way as for the entrance.

The three levels, highlighted during the excavations, cover both the moat as well as all the outdoor areas from south to north (Fig. 8a). The arrowslits in the



(a) (b)

Figure 7: a) Photos and b) planimetries from the artillery walkway.



(a)

(b)

Figure 8: a) Artillery walkway modelling with archaeologist annotation and corrections; b) Texture mapping of the lower level's eastern section.

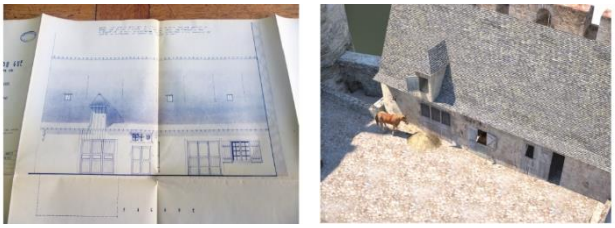
semicircular section, which no longer exists, were placed by extrapolating the regularity of their positions on the sides of the walkway. The stairs leading to the various levels were modelled according to the locations of the openings where they led. Since access to the gunner station located to the east is not approved, we modelled a stepladder in its place. Modelling the exit to the exterior raised several archaeological concerns. First based on an old lithograph of another Gate in Rennes (Du Crest de Villeneuve & Lorette, 1841), the modelling was adapted to the various improvements made by the archaeologist, so that it had both draw and dormant bridges, and would fit in as well as possible with the entire walkway (Fig. 8a). The lower levels were easier to model as they were still in relatively good condition (Fig. 8b). Concerning the textures, photos of the few remaining standing structures have been reworked to map the walls. Flat tiled shingles with ridges were employed to cover the roof. The overall floor was paved, though the pathway floor was made of slab shale and the dormant bridge was made of stone

2.4. Stable

Introduced in 2015 (Esnault, 2015a), the stables were originally located inside the walkway and modelled downstream of the 3D restitution process in 2017 (Esnault, 2018c). Thanks to newer plans (grounds and front) recently found in the archives (Fig. 9a), we were able to place this building more precisely, which before occupied a large portion of the walkway. Under the cart for sheaves that was used to store the straw, we added a horse to the front and a bale of straw (Fig. 9b). For the texture, we used a photo of a somewhat degraded sealant that we worked with Photoshop.

2.5. Curtain walls

The medieval curtain wall (to the south), still enduring today, had three geminated windows with central columns. They suggest the presence of a significant civilian building leaning against the inside of the wall. There was also rock at the base of the curtain wall, for which we modelled using a deformed plan (Fig. 10a).



(a) (b)

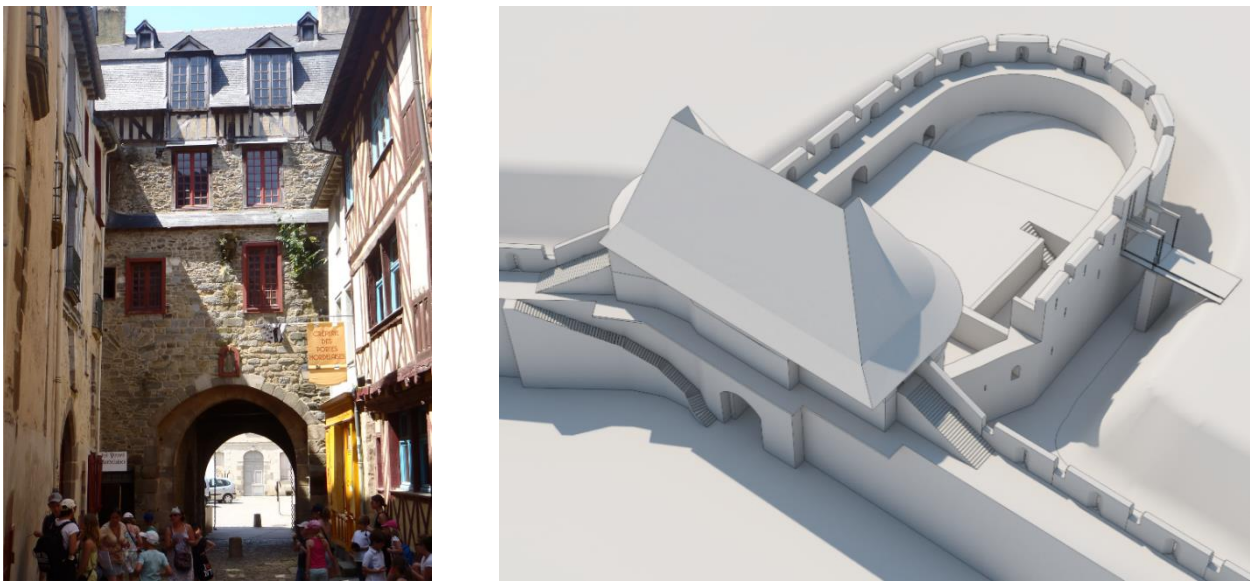
Figure 9: a) Drawing of the front facade (Esnault, 2016a); b) Textured rendering of the stable.

(a)

(b)

Figure 10: Photos and 3D models: a) The medieval curtain wall in the south; b) The ancient rampart in the east.

The smaller curtain wall, to the east, introduced in the basement an array of recycled architectural materials from important public buildings of the Early Roman Empire (280 AD). The tedious work of recreating the medieval sections with the Clone Stamp Tool was carried out in order to obtain the greatest realism possible (Fig. 10b).



(a) (b)

Figure 11: a) Photo; b) Current modelling of behind the entrance.

2.6. Behind the entryway

Even if the reconstruction was relatively advanced, we had decided not to continue to model behind the entranceway as we were still missing many elements. It was assumed that there was a long staircase from the passage to the medieval curtain wall (Fig. 11a). Even if some of the buildings were built in the same period, the current layout of the homes closest to the walls did not allow a detailed and informed understanding of what we could have expected when emerging through the entranceway at that point in time (Fig. 11b). This work could be resumed after a comprehensive archaeological study of the surrounding area had been completed.

3. Results

3.1. Integration in VR

In preparation for dissemination to the general public, a study on the design of interior spaces and lighting was carried out. At this stage, the objective was to build an authentic atmosphere, mostly hypothetical, but able to effectively convey scientific and historical information to the broad viewership. Through what we could obtain from libraries, we were able to create and place various components associated with defensive structures and living spaces. Considering that these elements were purely imagined (Resco & Figueiredo, 2014) and had no other function than decoration, we will not detail them here, but they were proved essential to supporting full immersive experience, presence and motivation to foster learner interest (Mortara & Catalano, 2018). The final restitution has been integrated into the cross-platform game engine Unity (Fig. 12). The various textured renderings presented above were also made using V-Ray. The 3D volumes were quite modest (152368 faces/193443 vertices in total). The work on textures was particularly important to increase realism, especially of the external stonework. We worked on 150 textures (612.9 MP in total and 4.8 MP per texture on average). This made it possible to develop the application without concerns for real-time lag. The recording of the voices for the pedagogical narration, whose scripting was supervised by the archaeologist, also took place during this pivotal moment of integration.

Simultaneously, several renderings were presented to the scientific (Esnault, 2018a & 2018b) and museographic communities (Le Cloirec, 2019). All these developments occurred during the preparation of the exhibition described below.

3.2. Public awareness

Prior to the exhibition's launch of "*Rennes, les vies d'une ville*" an explanatory panel illustrating only non-textured sections was firstly put on display near the gates (Fig. 13a). From a general perspective, this exhibition, which took place from October 20th 2018 until August 25th 2019, sought to pose a historical and anthropological question of its subject: what makes the city - from its foundation (around 10 BC) until the 2000s (Six, 2018). Based on numerous archaeological excavations carried out by the INRAP (French National Institute of Preventive Archaeological Research) and in conjunction with large-scale urban and spatial planning operations. It proposed a multidisciplinary vision and included mechanical, interactive and audiovisual means of better understanding the transformations of this territory.

As for the Portes Mordelaises, the objective was to offer visitors a virtual, immersive and interactive discovery of its development, with the following constraints:

- Absence of a permanently stationed mediator guide present in the exhibition rooms.
- Limit waiting times to avoid queues and frustration among visitors.
- Inform visitors in case of any impediment due to the use of other concurrent devices or equipment by visitors, or technological barriers.

A VR system was set up. It was based on two HTC Vive headsets without joysticks alongside a display of the graphics on a 2D screen (Fig. 13b).

The first summary of feedback from visitors to the exhibition was made over the first 4 months. During this period, there were 26432 admitted viewers, including 556 the day of its inauguration (2.1%). This represented an average of 210 passages per day over the course of 126 days. Initial observations indicated a positive surprise from visitors, a lack of apprehension about the headset and encouragement from visitors to one another. On the museum's guest book, the VR experience is regularly mentioned and the local press has indicated that "the most attractive thing being the virtual reality headset" (Ouest-France, 2019). At the end of the exhibition, 45850 visitors were accounted for. A census of the public was carried out by a polling and survey institute specialised in culture. To the question "what did you like best about this exhibition?", 12 answers emerged. Among them, the VR device was unquestionably noticed. However, it should be mentioned that some adults felt a lack of depth in the content (information and historical learning).

Two television (TV) broadcasts featuring the 3D reconstruction process were carried out. The first one was broadcast at the very beginning of the modelling process (Veillard, 2015). Following a study of the superposition of the existing on the hypothetical (Barreau et al., 2014), we applied our methodology in parallel with photogrammetry and various non-textured segments (Fig. 14a) (Debacker, 2019). This superposition was integrated within the "Immersia" VR platform (Gaugne, Gouranton, Dumont, Chauffaut, & Arnaldi, 2014) and presented in 2017 during the TV show "Xenius" (Fig. 14b) (Auer, 2017).

4. Discussion

Concerning solely the 3D aspects of production, the method we initially adopted as closely as possible to a complex multi-year excavation, particularly because of its anchoring in the heart of a growing city and thus perpetually under construction (Inrap, 2018). Over the course of the last six years of excavation, developments in research of recovery techniques, 3D modelling as well as a proportional theory of hypothetical segments of building reconstruction have all greatly evolved. Our work was consequently disseminated in several simple iterations, always systematically validated by the archaeologist, and was carried mainly with two tools relevant to our process: Autodesk 3ds Max and Adobe Photoshop. To be efficient, we wanted to reduce the number of software programs and increase their level of use (Delone & McLean, 2003).

(a)

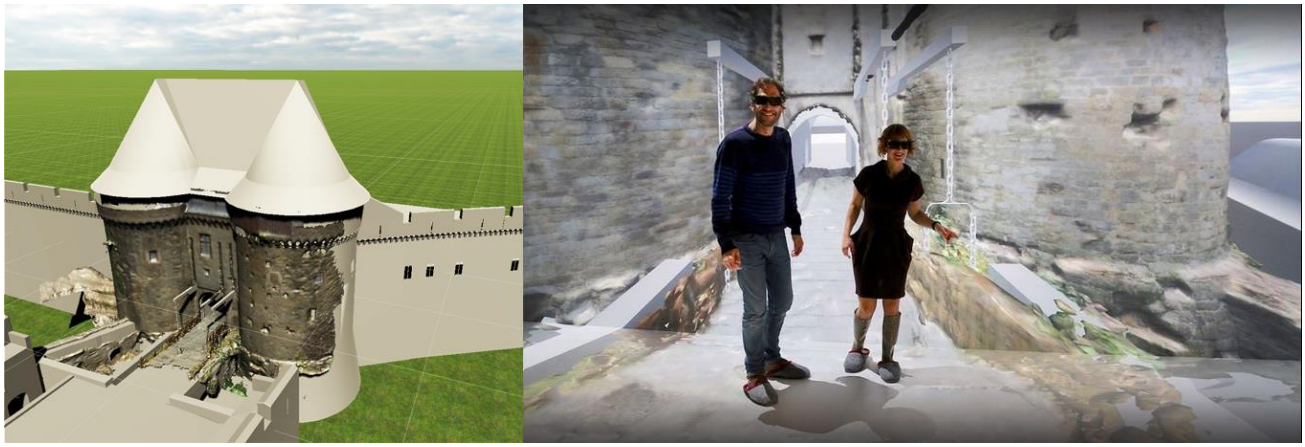
(b)

(c)

Figure 12: Final 3D reconstruction integrated in the cross-platform game engine Unity: a) Facing towers; b) Back to the towers; c) Inside the first floor of the West Tower.

(a) (b)

Figure 13: a) Children wearing hoods from a public school in Noyal-Châtillon-sur-Seiche (near Rennes) outdoors in front of an explanatory panel; b) VR headset used to present the 3D reconstruction of the Portes Mordelaises during the "*Rennes, les vies d'une ville*" exhibition (right ©A. Amet. Licence CC-by-SA).



(a) (b)

Figure 14: a) Superposition of the existing (photogrammetry) on the hypothetical (non-textured volumes); b) Presenters of the Xenius TV show within the "Immersia" VR platform.

For the applications of VR developed for the exhibition and TV program, here again, we wanted to use only the Unity tool. We did not test other virtual reality tools because we initially knew that this one would meet our needs. The added value, and therefore the goal, of the proposed method, was the complete adaptability to archaeological concerns with regard to the adequacy of requirements for a 3D production of sufficiently realistic VR integration (Barreau, 2017).

The main goals are scientific quality, and a timeline which parallels those of excavations as well as the allotting time for situational validation. We were not hindered by any technical obstacles, merely by archaeological interpretations and polemics. For example, the discovery of the stable was very late and the understanding of how the artillery walkway worked was quite difficult.

Formed by a tight-knit and intimate team, we believed that our method could correspond to Agile software development. Used for many years in the video game industry (Bosser, 2004; Koutonen & Leppänen, 2013), agile methods can also be used for remote sensing (Ahmad et al., 2012) and AR/VR applications (Hoda, Salleh, & Grundy, 2018). By analogy in particular to the field of video games, the archaeologist of our team had a role that would be close to that of a level designer. But in our case, the production time of the 3D models was high and the number of interactions in VR quite low. These involved the development of "simple" navigation through the 3D model and the triggering of a few sound elements when the user reaches specific locations. Thus the graphic designer-archaeologist collaboration was more important than those with the VR developer.

5. Conclusion and outlook

The 3D modelling allowed archaeologists to summarise their understandings of the building's organisation through a repeatable process. It made it possible to document excavation reports so to be assimilated into a public exhibition space, which hopefully shall motivate future intervention efforts. Going forward, we wish to model other periods, such as the Late Roman Empire, 10-12th, 13th and 14th centuries. Thanks to these models coexisting over several periods within a singular major monument in Rennes, we wish to develop a more comprehensive project covering the entire city, where several important excavations happened and continue being carried out (Inrap, 2019). Likely, we will change

our methods to make more inclusive use of historic BIM (HBIM). We will have to expand both our 3D production and archaeologist teams, making our particular techniques rather suitable to the task. We will be able to address more precisely the materials used and generate more semantically enriching complimentary materials, which have not been implemented in our approach yet. As to public awareness generally, we are additionally considering studying various mixed reality solutions, such as augmented reality (Carrión-Ruiz, Blanco-Pons, Weigert, Fai, & Lerma, 2019; Banfi et al, 2019) devices being distributed throughout the city.

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