APPLICATION OF REAL-TIME RENDERING TECHNOLOGY TO ARCHAEOLOGICAL HERITAGE VIRTUAL RECONSTRUCTION: THE EXAMPLE OF CASAS DEL TURUÑUELO (GUAREÑA, BADAJOZ, SPAIN)

LA APLICACIÓN DE LA TECNOLOGÍA DE RENDERIZADO EN TIEMPO REAL A LA RECONSTRUCCIÓN VIRTUAL DEL PATRIMONIO ARQUEOLÓGICO: EL EJEMPLO DE CASAS DEL TURUÑUELO (GUAREÑA, BADAJOZ, ESPAÑA)

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Highlights:

- The use of real-time rendering with ray tracing technology as a tool for heritage virtual reconstruction is proposed.

- The possibilities that the use of next-generation video game engines, specifically Unreal Engine, offer are evaluated in terms of their application in heritage virtualisation.

- The first results of the virtual reconstruction of the Tartessian site of Casas del Turuñuelo are presented, after using real-time ray tracing technology as a research method to create and review architectural hypotheses.

Abstract:

Virtual reconstruction has become a fundamental tool to study and analyse archaeological heritage, given its usefulness for both research and dissemination. Although the discipline has advanced exponentially in recent years, the workflow used in most jobs is still based on the offline methodology as the preferred rendering engine. In contrast, this paper proposes the substitution of this methodology with the new ray tracing in real-time rendering technology; specifically, the authors used Unreal Engine to develop virtual reconstruction work as a research tool during the excavation of an archaeological site, as well as to disseminate the results of the study of each phase. The aim is to exploit the advantages of the immediacy of calculating high-quality and realistic lighting and materials, as well as the interaction and immersion in the virtual model that this system for the development of video games offers. This paper highlights: a) the benefits detected when using real-time technology in heritage reconstruction during the work carried out to date, and b) its limitations and its future evolution with the development of the technology. To demonstrate the usefulness of this tool, the authors present the reconstruction project of the Casas del Turuñuelo site (Guareña, Badajoz). It is one of the best preserved protohistoric sites in the Western Mediterranean, which is why applying this technology to this case study was considered appropriate. The excellent architectural preservation of the Casas del Turuñuelo building is an extraordinary example to assess the usefulness of applying video game engines to heritage reconstruction. This settlement is one of the first known examples of this technology being applied to heritage, specifically, to the virtualisation of an archaeological site under excavation. This methodology and its improvements will be applied to the virtual reconstruction of this project as the excavation of this site advances; thus, one of the main outreach tools developed within the framework of Building Tartessos project will be made available to users as a final product.

Keywords: video game engine; real-time ray tracing; Unreal Engine; virtualisation; heritage

Resumen:

La reconstrucción virtual se ha convertido en una herramienta fundamental para el estudio y análisis del patrimonio arqueológico, dada la utilidad que presenta tanto para la investigación como la divulgación. Aunque en los últimos años la disciplina ha avanzado exponencialmente, el flujo de trabajo empleado en la mayoría de proyectos sigue basándose en la metodología sin conexión como motor de renderizado preferido. Frente a ello, el presente trabajo propone la sustitución de dicha metodología por la novedosa tecnología de renderizado con *ray tracing* en tiempo real; concretamente se ha trabajado con el motor de Unreal Engine, para desarrollar acciones de reconstrucción virtual como herramienta de investigación durante el proceso de excavación de un yacimiento arqueológico, así como para la divulgación de resultados del estudio de cada fase de trabajo. El objetivo es aprovechar las ventajas de la inmediatez de cálculo de una iluminación y materiales de alta calidad y realismo, así como de interacción e inmersión en el modelo virtual que este sistema para el desarrollo de videojuegos nos ofrece. Este artículo se presentan: a) los beneficios detectados al usar la tecnología de tiempo real en la reconstrucción del patrimonio durante los trabajos llevados a cabo hasta la fecha, y b) sus limitaciones y su evolución futura con el desarrollo de la tecnología. Para demostrar la utilidad de esta herramienta se presenta el proyecto de reconstrucción del yacimiento de Casas del Turuñuelo (Guareña, Badajoz). Se trata de uno de los yacimientos protohistóricos del Mediterráneo Occidental mejor conservados, razón que justifica la

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RECONSTRUCTION: THE EXAMPLE OF CASAS DEL TURUÑUELO (GUAREÑA, BADAJOZ, SPAIN)

ideoneidad de aplicar esta tecnología a este caso de estudio. El excelente estado de conservación de la arquitectura del edificio de Casas del Turuñuelo constituye un extraordinario ejemplo para valorar la utilidad de la aplicación de los motores de videojuegos a la reconstrucción del patrimonio. Este yacimiento es uno de los primeros ejemplos conocidos en el que esta tecnología se aplica al patrimonio, concretamente a la virtualización de un yacimiento arqueológico en proceso de excavación. Dicha metodología y las mejoras que vayan incorporándose, se irán aplicando a la reconstrucción virtual de este proyecto, a medida que la excavación de este yacimiento avance; así se ofrecerá un producto final que pueda ser puesto a disposición del usuario como una de las principales herramientas de divulgación desarrolladas en el marco del proyecto Construyendo Tarteso.

Palabras clave: motor de videojuego; trazado de rayos en tiempo real; Unreal Engine; virtualización; patrimonio

1. Introduction

Archaeological excavation is a destructive methodology. Each stratum excavated and each piece of material extracted from its context can never be returned to its original position, which is equivalent, as has been said on many occasions, to reading a book from which the pages are progressively torn out, making it impossible to read it a second time. For this reason, the documentation of the archaeological record has always been and will always be a fundamental task, as it is the only witness to the events that took place in a specific place and at a specific time. Its correct documentation and the compilation of all the data is a priority exercise in order to carry out a correct interpretation that will lead us to obtain an adequate historical interpretation.

Traditionally, drawings and analogue photography have been the two main tools for archaeological recording (Domingo Sanz et al., 2015). With them, all findings, both of structures or strata documented in the fieldwork, as well as those materials or objects recovered and analysed in the laboratory, were documented, thus covering the future needs of a review or study of a site that has already been the object of archaeological excavation and which, therefore, can never be re-excavated or documented at the stratigraphic level.

In recent years, this traditional recording system, which nevertheless remains the cornerstone of archaeological documentation, has been joined by new and pioneering methodologies which, while simplifying and reducing the cost of documentation work, have substantially improved the quality of the graphic record, opening up endless possibilities for the user, not only in terms of data collection, but also in terms of their processing and subsequent use (Markiewicz, 2022; Maldonado, 2020). As a result, digital photography was already a true revolution in archaeological recording, which was quickly joined by photogrammetry, and the construction of 3D models from the use of laser scanners, tools that have not only made us advance in the strictly scientific field, but have also submerged archaeology in the field of dissemination, allowing visitors to enter an archaeological site without the need to travel to it (Caro & Hansen, 2015; Delgado & Romero, 2017).

So we are currently witnessing an increase in the analyses and interpretations of archaeological sites thanks to the incorporation of digital applications and 3D (Gisbert, 2019) reconstructions, tools that allow us to work with reversible models that can be easily updated according to the new interpretations that may arise during the research. This makes it possible to reconstruct the sites and their contexts in a plausible way on the basis of what has been documented, by putting on a model what has previously been imagined with the aim of checking its reliability and revising it in the light of possible parallels, the construction technique

and the materials used. This process helps to identify possible areas of conflict or gaps in information, so that options can be discussed and one or more working hypotheses can be drawn up. Serve as an example the results obtained in the "Etruscanning3D" project (Hupperetz et al., 2012; Pietroni & Adami, 2014), the reconstruction of the landscape of the Tiber Valley North of Rome in the 8th century AC (Pietroni et al., 2013), the experience in the creation of virtual content for museums of the Galicia Dixital projects (Hernández et al., 2008), or the Tiwanaku proposal, which combines design technology and 3D printing for the study and dissemination of heritage (Vranich, 2018).

But the possibilities of 3D modelling do not end after its application in the framework of research, in such a way that it has become a powerful tool for informing the general or specialised public about the progress of a project and its nature as an active site, thus transferring the knowledge of the site studied to society through an inclusive language. In this way, the result of the detailed study of a site and its expression in a final model can be transferred to the creation of digital experiences that enrich those spaces destined for collective knowledge (Smith et al., 2019).

With this dual scientific and informative objective in mind, this study aims to go a step beyond 3D modelling, as it proposes the incorporation and application of real-time rendering technology with Unreal Engine to the study and reconstruction of archaeological heritage, thus offering the user an alternative to the use of traditional 3D modelling systems. To demonstrate its usefulness and the excellent performance that the use of this tool offers, we present the first results of its application to the analysis of the site of Casas del Turuñuelo (Guareña, Badajoz), an enclave belonging to the final phase of the Tartessian culture and which stands out, among other reasons, for its excellent state of preservation (Celestino & Rodríguez González, 2020). With it, we aim to contribute to historical and methodological enrichment, following in the wake of other studies which, prior to our contribution, have already opened the way to the use of digital applications in archaeology (Berrocal et al., 2021).

2. The site of Casas del Turuñuelo (Guareña, Badajoz, Spain)

The site of Casas del Turuñuelo is a monumental earthen building, located in the middle Guadiana valley and dating from the fifth century BC. At the end of its existence it was burnt, abandoned and buried under an artificial earth mound that has served as a capsule, protecting the building from deterioration (Fig. 1) (Rodríguez González, 2018). This system of concealment to which all the burial mounds of the Guadiana were subjected means that today the site

of Casas del Turuñuelo is in an excellent state of conservation, being the first protohistoric building in the Western Mediterranean that still has its two floors standing.
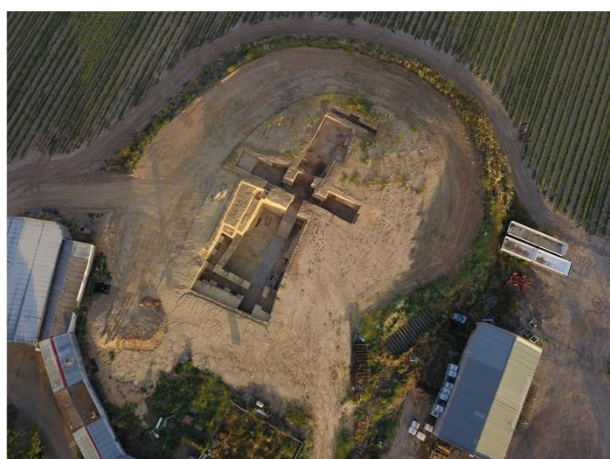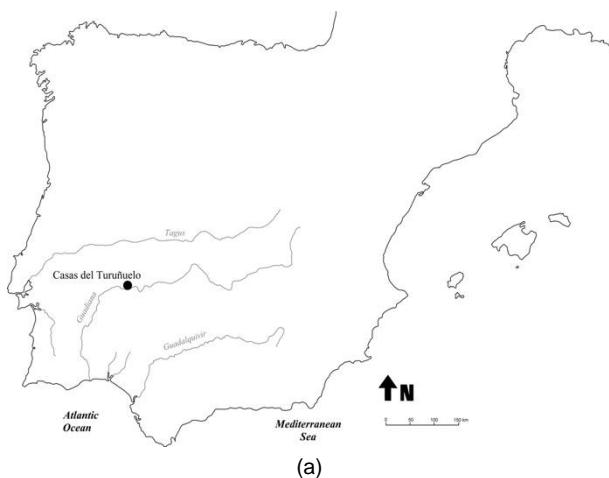

(a)

(b)

Figure 1: a) Map showing the location of the site of Casas del Turuñuelo (Guareña, Badajoz), and b) aerial photograph of the burial mound at the end of the archaeological excavations in 2018.

Since excavation work began in 2014, only 30% of the site has been uncovered; however, the remains recovered are of great architectural and material significance. To date, we know of three of the rooms located on the first floor of the building. Room 100, measuring more than 70 m^2, has been identified as the main room, both for its dimensions and for the ritual elements documented in it, such as the altar in the form of a bovid skin or the basin/sarcophagus; although, without a doubt, the most outstanding element in this space is the existence of a brick vault used as an architectural solution for the covering of this room (Rodríguez González & Celestino, 2017). The next room is S-1 or the "banquet room", used for the preparation of food for the celebration of a ritual banquet to celebrate the closing of the building; fine ceramics were documented in the room, which would have been used for the consumption of food and wine that would have formed part of the banquet (Rodríguez González & Celestino, 2019). The third room is located to the north and its excavation is still incomplete, although it has been possible to exhume the remains of a buried individual, accompanied by a sumptuous array of materials, including three bronze 'braziers' and several iron tools.

These rooms are accessed from a small vestibule that also leads, from the east, to the monumental staircase that connects this upper space with the ground floor. The staircase at Casas del Turuñuelo is a unique example of protohistoric architecture, not only because of its dimensions and structure, but also because its lower steps were made with lime mortar, the oldest evidence to date of the use of this material at a site on the Iberian Peninsula (Rodríguez González *et al.,* 2020). The staircase leads to a large open space, a 120 m^2 courtyard, on the floor of which a hecatomb-like animal sacrifice was documented, which must have been held in parallel to the ritual banquet that preceded the closing of the building (Celestino & Rodríguez González, 2019). Finally, although the archaeological excavations have not been completed, we only know part of the perimeter corridor that surrounds the courtyard to the southeast, and the total dimensions of the building and its internal organisation are still unknown.

3. Planning of the project

The outstanding number of architectural discoveries that make the site of Casas del Turuñuelo a unique example of the protohistory of the Iberian Peninsula justify its choice as a test laboratory for the implementation of real-time ray tracing rendering technology with *Unreal Engine.* Its application to the study of archaeological heritage is a novelty within Virtual Archaeology, as it is the first time that this tool has been used in the investigation and reconstruction of an archaeological site. In this case, moreover, we are dealing with the reconstruction of a site in the excavation phase, so it is still a dynamic example, which makes this exercise an interesting technical and methodological challenge.

The initial approach of this project is to evaluate the possibilities that this work system offers in order to create a base on which to incorporate technologies derived from the leisure and simulation fields that are in constant development. Working on this platform allows us to take advantage of the benefits that this technology offers us in terms of its application in other professional sectors, such as heritage, not only enjoying the technological innovation that it offers us, but also the possibility of bringing science closer to all types of public, an advantage that will increase as the project reaches a higher degree of development.

Virtual reconstructions are traditionally undertaken on the basis of the data derived from the excavation when these are definitive and the site or enclave is almost completely known (~90%), in order to offer a complete view of the reconstructed site, as the purpose of these reconstructions is almost always focused on dissemination to the general public, whether with an informative, educational or tourism function (François *et al.*, 2021). In contrast, in the case study of Casas del Turuñuelo we have opted for reconstruction in phases that will evolve and grow in parallel with the excavation, so that the reconstruction will be expanded and updated on the basis of new data from each annual campaign, growing as new areas of the site are excavated or studied. At the same time, this will allow the reconstructed parts to be revised, as the presence of new data or evidence will make it possible to develop new approaches that will lead to new interpretations.

The use of real-time ray tracing as a rendering technology with Unreal Engine has given us the opportunity to make a qualitative leap from traditional 3D to a dynamic virtual world in which we can move around like in a video game, being able to walk around the interior and appreciate the scale with a first-person perspective. We have therefore established a technological base, with multiple subsequent applications, while playing with its advantages in the development process of a virtual environment that allows us to work on the details, textures, move objects and review structures and architectural hypotheses, observing the result in real-time, which speeds up the reviews with the different experts who are leading and supervising the project, and all this with a quality very similar to that of a traditional pre-rendered 3D model.

In addition to the advantages already listed, real-time ray tracing is a rapidly developing technology has great potential as a basis for the creation of more immersive experiences. This will not only allow us to work on the hypotheses more efficiently, but also to make quality dissemination so that the public can enjoy the experience of visiting a site as it was, both in formats that are easy to publish, such as images or videos, and in future Virtual Reality applications. These currently have certain limitations due to the power of the hardware they use; however, given the speed at which the development of this technology is advancing, it promises a future with great experiences within the reach of most of the public.

4. 3D offline vs 3D real-time

Real-time rendering engines, also known as the engines that generate navigable 3D environments in video games, have experienced an enormous progression in recent years, which has taken the quality of lighting, materials, effects and computing power to a higher level. This is due, in part, to the evolution of graphics hardware (graphics processing unit, GPU) and the commercial rise of next-generation gaming systems, both on high-performance personal computers (PCs) and game consoles. As such, this evolution cannot be understood without looking closely at the growth and development of the entertainment industry, which in turn has sometimes transcended the boundaries of entertainment to penetrate environment simulation systems. Now, real people can face complex situations, those that if they were real would endanger their physical integrity, thanks to the existence of simulated environments where they can train work processes or safety protocols.

The basic difference between these two types of rendering, which we will call offline and real-time, is that the process of calculating the final image that we want to obtain of our virtual environment is carried out at different times and using different processes. Thus, while in the offline type the rendering of the virtual environment is performed at specific times at the user's request, the real-time rendering uses the GPU to constantly calculate the position, texture and incidence of light on all objects that are in the camera view. To do this, the GPU requires a great deal of computing power, as it is constantly tracing rays that determine how the light hits the geometry of objects, while simultaneouslydisplaying them on screen with their materials and the scene lighting without interruption. All this is done at the same time as handling other added factors such as atmospheric effects, particles and image style post-processing.

The real-time engine renders an image every few milliseconds (~16 ms for a rate of 60 frames per second (fps), 33 ms for 30 fps), giving us a correct and fluid visualisation of our scene on screen that corresponds to our final rendering; while the offline rendering offers us a less detailed visualisation of our scene on screen, which forces us to work with a synthetic view of the objects, without the detail of the materials and without the final lighting. With this system, we do not obtain a definitive image of our project until we proceed to the rendering of the image, a process that requires longer processing time than the one used in the real-time system.

The huge development of GPUs in recent years has increased the interest in real-time rendering by using this hardware to take advantage of its performance. This has meant that most offline rendering engines have opted to offer this alternative calculation, generally based on *Pathtracing*, a raytrace solution that refines the resolution (the longer the processing time, the higher the quality of the result). This system is making it possible to produce final images more efficiently than with central processing unit (CPU), while interactively displaying on screen a result very close to the final rendering. However, it still requires a great deal of hardware power and a much longer time to display a finished image compared to the resources required by real-time rendering, which is visually immediate and without interruptions for the user.

Offline rendering has always been a superior method in terms of the amount of geometry it is capable of rendering in a scene, in addition to its ability to render complex textures and high-quality lighting. But the emergence of ray tracing in real-time rendering engines in 2019 introduced a high-quality lighting system with Global Illumination (GI) that calculates the secondary bounces of direct light, in the same way as the best offline rendering engines. This development has caused a great visual rapprochement between the two systems, by accentuating the shading realism, despite the fact that technically they are two very different working environments. Progress in ray tracing lighting has also been enhanced by the commercial development of Nvidia's new generation of graphics cards with Turing architecture.

Among the advantages of real-time processing is its immediacy. The final result is visible on screen throughout the production process. This allows us, for example, to make changes in lighting, a method that is currently used in television or film productions where, through the use of high-resolution screens, virtual environments can be projected to replace the traditional chromas, which require a complex subsequent editing process.

However, one of the most decisive factors in choosing to work in real-time comes from its status as a videogame engine, which allows us to use the full range of physical characteristics and the great power of programming features, events or interactions, as well as the high computational speed in particle systems and effects. This is the case of the possibility of moving around our model in the same way as in a videogame, moving through our work environment with a first-person view, which allows us to have a realistic view of the scale, correctly appreciating the dimensions and proportions of

the scene. This model has only one limitation which we must always bear in mind: the camera view, as it will never be faithful to the human field of vision.

Furthermore, the enormous speed in the calculation of video sequences, even at higher resolution and quality than that shown in real time on screen, makes it possible to eliminate one of the major bottlenecks of traditional 3D production. We are referring to the dependence on render farms, installations composed of many rendering workstations in parallel that increase production costs, which can be in-house or outsourced, but which are necessary to render animation sequences of complex environments in reasonable times.

In contrast to the advantages listed above, there is a major drawback. Real-time engine editors are not designed to model and map geometry, as they lack a 3D modelling environment. Although tools are progressively being incorporated for minor modifications to the geometry, it is still essential to do the work of constructing the geometry and preparing it for texturing in an external editor, following the traditional method. The result is a more complex workflow that requires the use of several 3D software packages during the process, by exporting/importing the model in each revision or update, which makes it necessary to develop robust working strategies in complex models.

Finally, in order to draw some conclusions about the advantages and disadvantages of both working methods, it is necessary to consider the simultaneous development of other technological applications whose enormous possibilities within the field of virtual archaeology are only beginning to be grasped: all the applications in the field of Virtual Reality (VR), Augmented Reality (AR) and Extended Reality (XR) that work, a priori, with the same technical requirements of real-time rendering and for which numerous programmes are available, many of which are freeware. There are already good applications of VR in the field of heritage with representations based on photogrammetry, with advanced locomotion systems, installed in museums or interpretation centres, as is the case of the Motilla del Azuer (Torres Mas *et al.*, 2022) or the Forum of Augustus (Ferdani et al. 2020). However, some of these applications are still limited in their use on mobile devices due to their low graphics power, for example in VR, due to the requirements of large screen resolutions and high framerates that make it necessary to rely on a high-performance computer.

But the advantages of producing our virtual environment in real-time are even more evident when we can develop immersive experiences based on visual footage for VR devices or CAVE (Cave Assisted Virtual Environment) type systems, as in the case of Ullastret, where they apply the same product to these two platforms with the relevant technical adaptations (Codina Falgas *et al.*, 2017), or screen projections of a tour through a photogrammetric model as in the case of the Santimamiñe Cave (Barrera Mayo & Baeza Santamaría. 2010). And so, once the technical limitations are overcome, the goal is to have a solid model entirely developed with a real-time rendering engine that allows us to translate it to a VR environment on multiple platforms for all types of users (Andreu *et al.*, 2022) and for different areas of knowledge (Caarls *et al.*, 2009).

5. Working methodology used in the reconstruction of the Tartessian site of Casas del Turuñuelo

Virtual reconstructions use different tools dedicated to different specific technical tasks that work as a set of work processes, which constitutes our workflow. There is no single workflow for each type of work, so we tend to combine processes from different industry sectors that share similar objectives to ours, in order to find the ideal combination of processes that suit our needs.

In our case study, the virtual reconstruction of the Casas del Turuñuelo building is conceived as an experimental project in which, for the first time, the usefulness of the application of the real-time working method is evaluated with a view to its incorporation as a regular tool in the development of hypotheses during the research process and in the dissemination of its results. To this end, we have designed a work methodology consisting of two phases with differentiated working environments. The first phase involves the design of one or more working hypotheses in which the architecture is analysed at the level of simple geometry with the aim of validating a first model that serves as a starting point. Once the model has been created, we can move on to the second phase, which involves the virtualisation of the model, the creation of well-defined textures and materials, the integration of lighting and any other effects necessary to achieve the desired final appearance.

In the first phase, the working system does not differ greatly from the reconstruction procedure used in 3D offline rendering. As we announced in the previous section, it is necessary to work with a conventional 3D editor, as the real-time engines do not have 3D modelling environments. For this, we can use any industry-standard software, such as Blender, 3D Studio Max, Maya, Cinema 4D, etc., as they all have a similar working system, adapting to technical standards without any problem, despite being more or less specialised and focused on certain sectors. For our model of Casas del Turuñuelo, we have chosen to use 3D Studio Max v. 2020 due to the experience accumulated with this software, although the use of Blender is recommended as it is freeware, which facilitates access to it for any user.

Once we had built our initial model, we moved on to the second phase of the project, the aim of which was to work with the model in a real-time rendering environment. For this part of the process, we selected Epic Games' Unreal Engine, working on v. 4.24 to 4.27, as it is one of the software applications that has had the greatest impact on different sectors of the digital industry in recent years, with a major expansion in the leisure and simulation market, as it has incorporated the new real-time ray tracing calculation system since v. 4.22. It is a free software for which only royalties are paid for sales volume in the case of developing a paid product, such as a video game, apart from addons, models and utilities that can be acquired from Epic Marketplace.

Ideally, these two phases of the process would be carried out simultaneously. To do so, we would have to work with a definitive hypothesis, with a volumetry that was already conceived in its final format, so that it would not have to be reconsidered in the future. However, this is not usual, less in an example such as that of Casas del Turuñuelo, a living site, in the excavation phase.

Therefore, our main hypothesis is under constant review and development, in parallel with successive excavation campaigns, and is therefore always subject to new data derived from ongoing research.

The process of creating and modifying geometry in 3D Studio Max and importing it into Unreal Engine is a process that will be carried out periodically throughout the development of the project due to this need to review and update the model in each campaign. It is essential to create a coherent and robust work system, with tools that help to streamline and automate processes, while ensuring that all the elements of the architecture are well referenced in a source and that they are always updated in the same position. To do this, it is essential to have a battery of working tools that allow us to speed up these processes and create a good work plan around how to develop the model and what will be the export/import times in our real-time environment. It is therefore essential to make a thorough analysis of the parts in which we must differentiate the various geometries, based on spatial, structural, textural and contextual criteria.

One of the most important spatial criteria is the correct subdivision of areas or rooms, for which we will create as many separate geometries as necessary to work comfortably, so that we avoid that the updating of one part of the building invalidates others when revising the hypothesis. The structural criterion obeys the need to keep separate the structural elements of the part built with mouldable materials, being in this category where we must include not only the wooden structures, beams, plant elements or similar, but also all the mobile enclosures and their supports, in the case of the wooden frames and other structures of superimposed materials. In the case of Casas del Turuñuelo, a good example would be the stairs in the courtyard or the channelling, as well as the slabs and cladding. At this stage of the project, although the real architecture presents solid structures composed of different materials, our virtual model does not present solid materials, but rather skins without substance, so it is important, within each of the areas, to differentiate the interior surfaces from the exterior ones, as well as their points of union. This will facilitate the task when applying criteria for their texturing, thus being able to easily differentiate elements with different surface finishes or which are likely to require different materials for technical reasons, despite sharing a similar appearance between them.

As far as the context is concerned, we will take into account the terrain on which the site is located, in our specific case a building, with the aim of assessing the possible use of the topsoil level as pavement or the possible existence of elements that may have been excavated in it, such as a moat, the best example of which is documented at the neighbouring site of Cancho Roano (Zalamea de la Serena, Badajoz, Spain). In this sense, the reconstruction of the environment of Casas del Turuñuelo is, for the moment, premature, as we do not know the limits of the building, its dimensions or the existence or not of auxiliary structures related to the main building.

For the first stage of the work, it is essential to have the advice of experts, in our case archaeologists and architects, who contribute to the design of the starting hypothesis, so that the virtual reconstruction is as close as possible to reality. In the case of the site of Casas del Turuñuelo, the basis of the model has been designed on the basis of the complete photogrammetry of the excavated part of the site to date, combined with the superimposition of the planimetries taken in situ by the team of archaeologists (Fig. 2) and batteries of photographs taken during the excavation work in order to have visual confirmation of all details. This allowed us to establish the correct orientation of the construction and its scale, as well as to set a point of origin for the correct correlation of all the data to be updated or incorporated in the future. This step is essential if we want to maintain consistency, both for the initial geometry export/import sequence and for future updates.
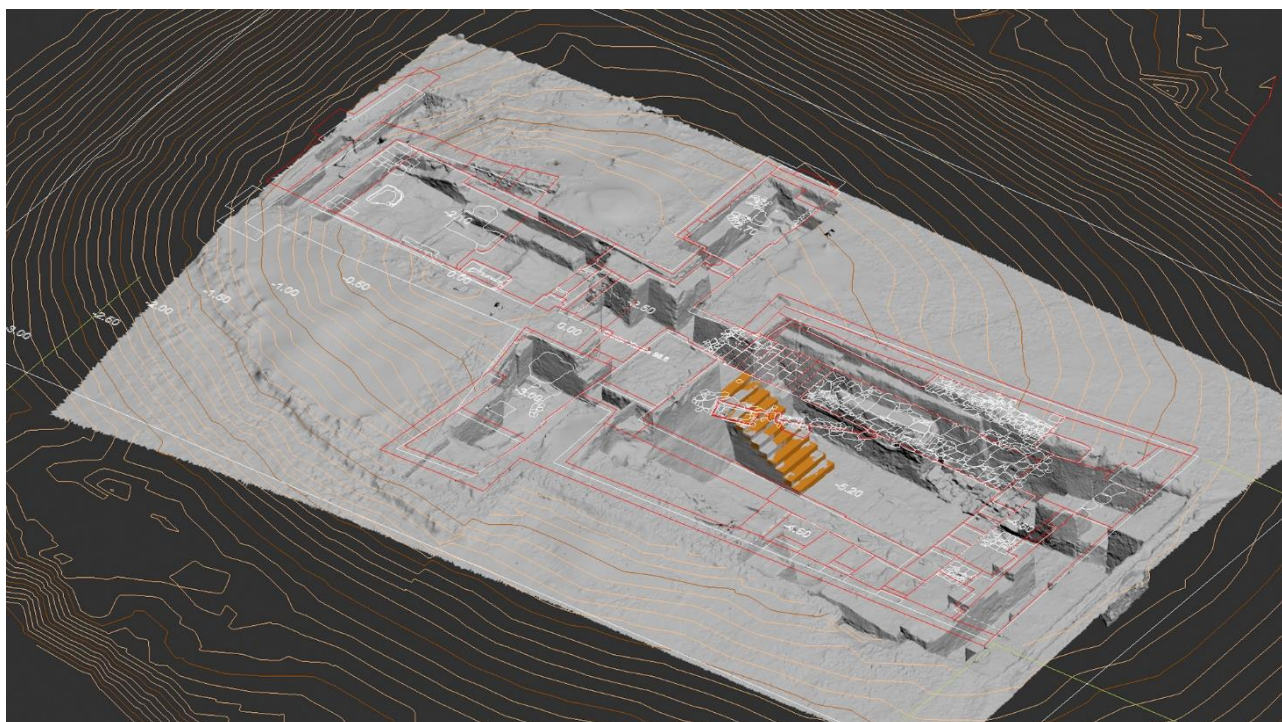

Figure 2: Photogrammetric model with the planimetries of the Casa del Turuñuelo site and the topography superimposed.

Figure 3: Basic 3D model built on photogrammetry as a starting point for our hypotheses.

We built a simple model over the photogrammetry that reaches the height of the upper stratum of the tumulus (Fig. 3). To do this, we looked at the two sections flanking the stairway, which are correctly represented in the photogrammetry, as they are the two architectural structures that are best preserved in elevation within the site. Based on these, we have been constructing the hypothetical volumes, while at the same time adding details to the geometry, such as enclosures or roofs, a task for which the project relies on different teams of experts. However, in order to reach a simple volume hypothesis that is plausible and suitable for continuing the work, it is essential at this stage of the process to consult architectural parallels, in the case of archaeological sites that have already been excavated with which our virtualised site shares chronological and cultural characteristics (Fig. 4).

Photogrammetry also allows for the visual analysis of the structures while it is easy to build simple sections with a view of their external face and therefore be able to resolve the composition of their internal structures with real measurements. A difficulty arises in this part of the project, as on occasions, we will have to project the hypothesis by placing the structures in what would be their original position, correcting the damage, deviation or collapse that they currently present. This is the case of some walls, which are slightly displaced, or of the pavements, which are often sunken, so that they have lost their original elevation (Fig. 5).

These preliminary geometries will be revised in order to validate the main hypothesis. During the project process, revisions can be made through images obtained from the model with offline rendering, from

sections or construction details, or by exporting them directly to the real-time engine as simple models, so that they can be quickly visualised in Unreal Engine with a realistic first-person perspective. In this way,

(a)
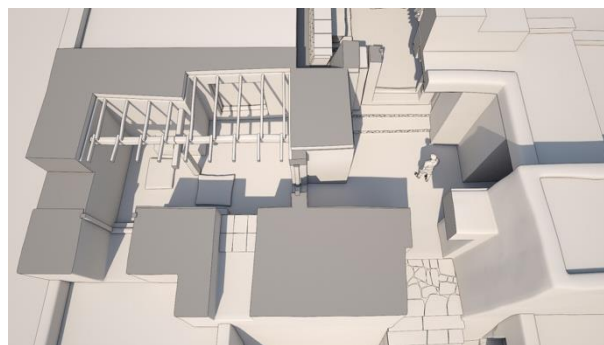
(b)

Figure 4: Construction of the main hypothesis by solving the building structures: a) room 100; b) room S-1.

Figure 5: Geometrical hypothesis interpreting displaced structures on the photogrammetric model.

the team of archaeologists can carry out a series of revisions of the model in simple videoconferences via streaming, viewing the interior of the model in an immersive way, without it being necessary at this stage to carry out detailed work on the lighting or to create specific materials, such as textures.

With a validated main hypothesis (Fig. 6), it is time to go into detail, separate constructive elements, resolve gaps between the different parts, reshape surfaces to give the architecture a more organic appearance and prepare the geometry for texturing, with UV coordinates in the different channels enabled according to their application. For this, the objectives must be clearly established, according to a working strategy that establishes the
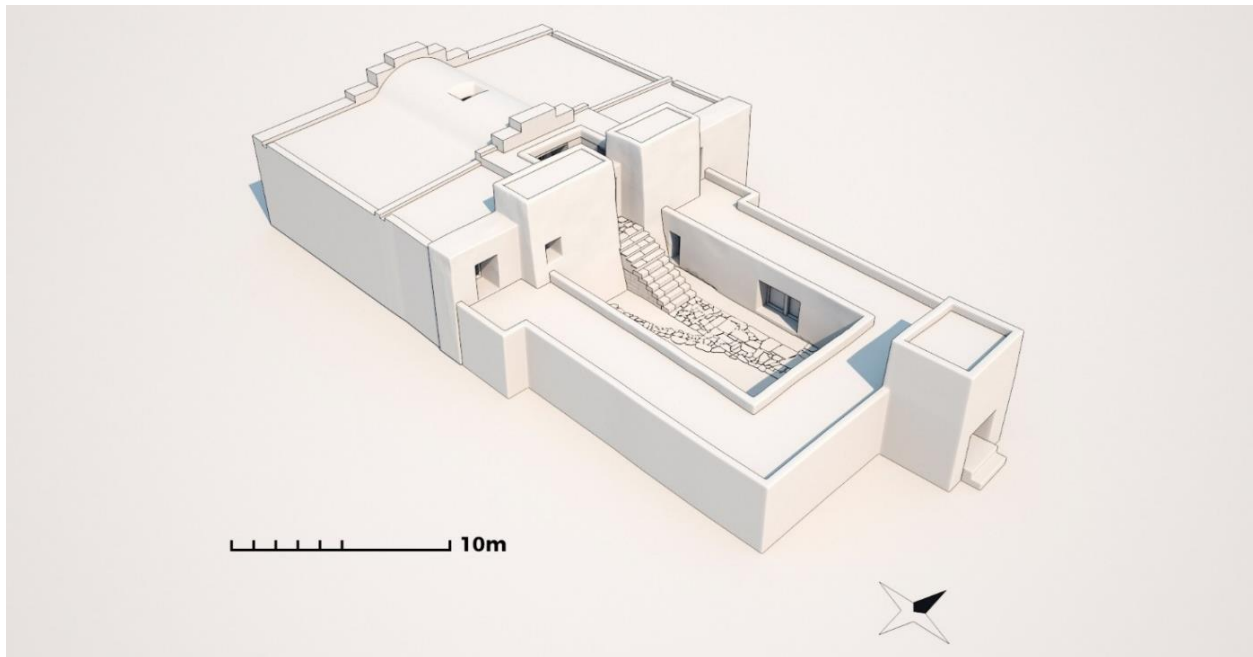
(a)

(b)

Figure 6: Final model of the main scenario prepared for export: a) complete building; b) courtyard view.

number of different textures to be created, the necessary resolutions, as well as differentiating the textures that will be common and reusable in different elements, from those that will be unique and specifically created for each object.

In this last phase of the process, we must prepare all the elements according to the technical requirements necessary for real-time rendering, taking into account the number of polygons and the homogeneity of the texel density. In our case, the objective is to prioritise visual quality over hardware performance, so we will have to follow the best practice recommendations set out in our workflow to find the right balance in the optimisation of our work.

Once the model is ready to tackle the second stage of the project, we will proceed to export our detailed geometry to Unreal Engine to create a new virtual model (Fig. 7). To do this, we will start from a project created for this purpose, with the basic characteristics necessary according to the lighting technology chosen and other determining factors to establish the format and the platform for the use which, for the moment, we will keep in its version with higher specifications to work without technical limitations taking advantage of all the computing power of the GPU.

During the process of creating materials, lighting and detail adjustments, we have always used real-time ray tracing. Its standard quality level offers a perfectly realistic on-screen display. With this system, the work is very agile and interactive, as we can always visualise the result on the screen with a medium level of optimization, parameters that will be specified according to the image quality objectives that are defined in the premises of each project (Fig. 8).

For the lighting, we have used Unreal's system so that the direct sunlight is positioned according to the latitude and longitude of the site, with the date and time that we indicate (Psaila & Rolfo, 2012). With this system, we can simulate the movement of the sun throughout the day for a specific date of the year and therefore check its reach through the openings of the building. However, it goes without saying that this simulation responds to the current solar position, so one of the pending tasks of the project is the programming of the calculation of the correct sun position by modifying the blueprint (visual scripting system within Unreal Engine), with the aim of applying the equinoctial precession to obtain the correct solar position at the time of use of the building, about 2500 years ago.

One of the problems we may face when simultaneously viewing the interior and exterior of the building is the abrupt changes in light in the transitions due to the camera's automatic exposure changes (Murdoch *et al.*, 2015). To avoid this, lighting has been designed with supporting lights to enhance the penetration and bounce of sunlight into the interiors through the openings, while the lighting of the darker spaces has been reinforced with the incorporation of skylights that add light and colour temperature contrast. This has allowed us to use a hybrid system combining

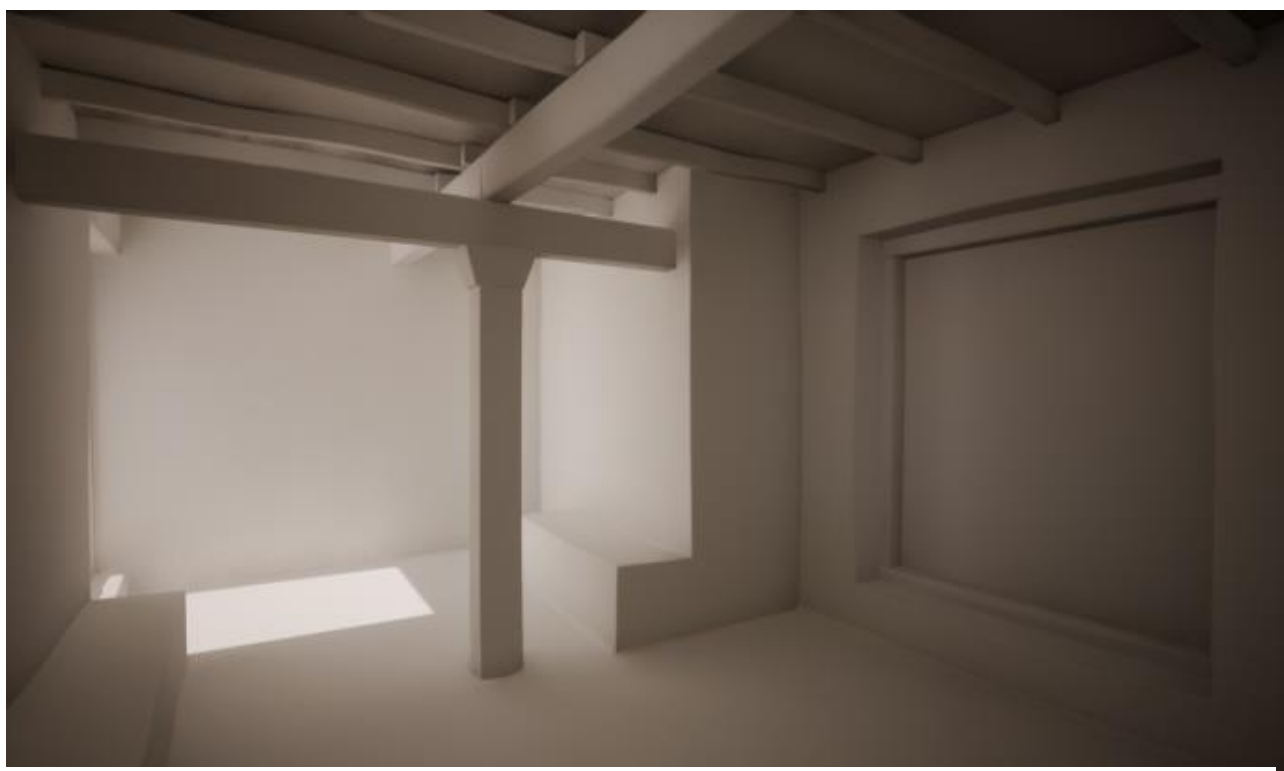**Figure 7:** Geometric model imported into Unreal Engine.

Figure 8: View of the basic lighting for real-time rendering.

real-time ray tracing and lightmapping with the aim of using indirect light as a precomputed system. In this way, we can improve GPU performance and obtain smooth navigation through the model in first-person mode once the model is finished (Fig. 9). In addition, to complete our virtual environment, we have worked on some details and effects that will allow us to give a little more life to the first phase of the reconstruction. This is the case with the particle systems for the skylights and the fire, the accumulations of ashes and other elements on the exterior, taking advantage of all the available tools.
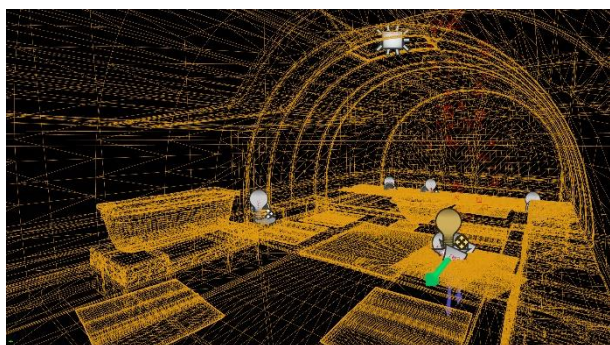
(a)
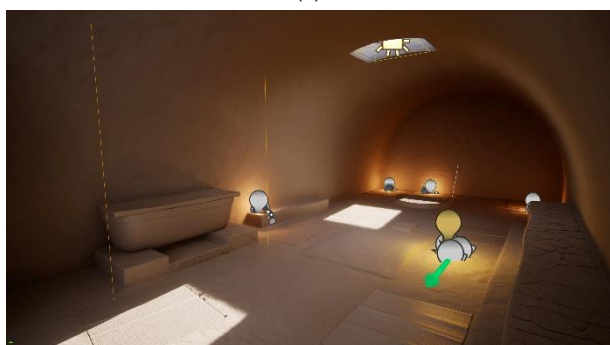
(b)

Figure 9: Detail of the hybrid lighting scheme: a) wire preview; b) shading preview.

For the creation of textures, we have used a mixed system combining the more traditional systems, such as Adobe Photoshop v. 23.4, with different tools from Adobe Substance (initially Allegorithmic Substance) and Substance Alchemist with Photoshop, in some cases, and Substance Painter and Designer for others. The latter combination is used especially for elements with specific textures created by designing directly on the model with Substance Painter, as in the case of the altars and homes, which were treated as independent elements of the architecture. Working with real-time materials is very agile as the instant rendered visualisation makes it possible to create variations quickly, make fine adjustments to parameters and textures, and observe how they change under different lighting conditions by varying the time of day and their reaction to indoor lighting conditions (Fig. 10).

With regard to GPU performance, we should bear in mind that the virtualisation project model proposed here as an example has contained dimensions, but with high-resolution textures so as not to lose detail in the foreground when we are in first-person view mode. In the early stages of the project, an Nvidia RTX 2080s graphics card was used, with sufficient performance

under normal conditions, and then we switched to the latest generation Nvidia RTX 3080ti, which significantly increased performance.

The final result has become an excellent working tool for both scientific and informative purposes. In this second aspect, we have also benefited from the advantages of using the real-time ray tracing engine by working with very short rendering times of images and video sequences in high quality compared to the offline system. In this way, we have obtained realistic results using the physical cameras of Unreal Engine, which offer a behaviour very close to reality, as they are well adjusted to the physical laws of optics and do not allow forcing impossible situations with their system of lenses and sensor formats that respond like real cameras (Fig. 11).

The aim is to continue working on the new phases of development with a view to creating immersive applications that will allow virtual visits, once a significant part of the virtual reconstruction has been completed, focused both on the public who have access to the site and those who wish to explore it without having to travel to it. These virtual tours will be available in different formats that have not yet been defined. However, the quality of VR points to its full development in the near future, when both hardware and software have matured and it will be possible to design better quality experiences for the non-specialist user who does not have high-performance equipment (Fig. 12).

In the same way, in future phases of the project, work will be carried out on a higher-quality streaming visualisation system for the review of the real-time virtual model by the supervisors and experts participating in the project, with the possibility of implementing multi-user VR solutions.

6. Discussion

With the release of version 5 of Unreal Engine (UE5) in early access in May 2021, a major evolution of this software package was presented with a series of improvements with new technologies under development that, in the immediate future, promise a revolution in the real-time workflow. The combination of these developments with the ever-improving performance of GPUs bodes well for a future in which all barriers to virtual representation will be broken.

Of all the improvements in the evolution of the Unreal Engine, including powerful animation tools and very advanced particle systems such as Niagara, we will highlight two sections that we can say are the basis of any virtual environment and that form the corpus of this great technological leap that UE5 represents. We are referring to the lighting system with Lumen and the geometry management system with Nanite[1].

Lumen is a global illumination and integrated reflections system that offers robust, instantaneous calculation of direct light and multiple secondary bounces for indirect light, delivering hyper-realistic lighting with great hardware performance, via a hybrid ray tracing system

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[1] The technical documentation corresponding to the characteristics of UE5, Nanite and Lumen, can be checked at: https://docs.unrealengine.com/5.0/en-US/RenderingFeatures/ (03 August 2022).

(a)

(a)

(b)
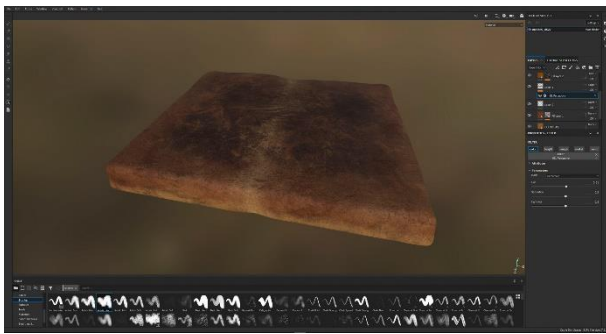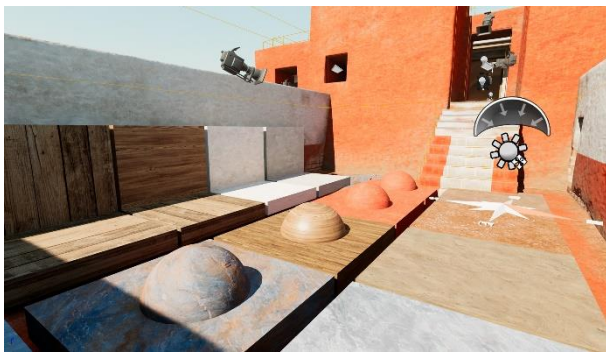
(b)

Figure 10: a) Work on secondary structures, such as altars and hearths, in Substance Painter; b) Interactive real-time work on materials with changing light conditions.

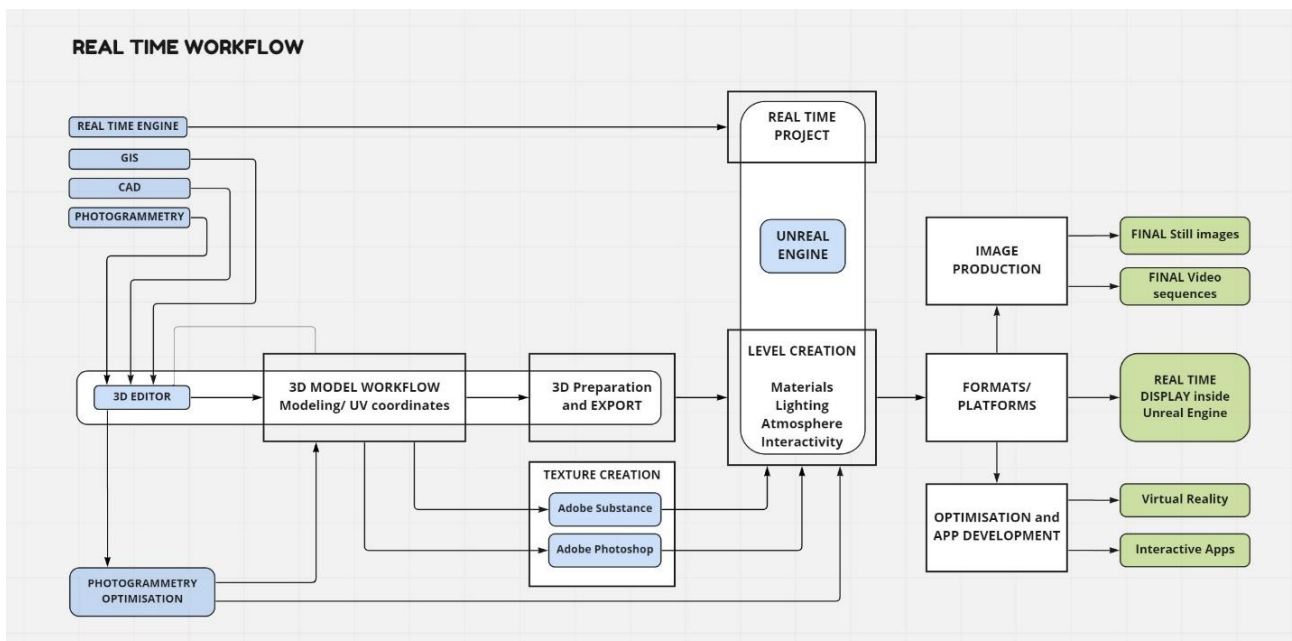**Figure 11**: Views with Unreal Engine physical cameras: a) final interior; and b) exterior.

Figure 12: Diagram showing the work cycle used for heritage reconstruction with real time ray tracing technology.

that works excellently with atmospheric systems. It exceeds the standard ray tracing light quality of the Unreal Engine v. 4.2 versions by several orders of magnitude, and requires no alternative calculations or tricks to improve its performance. In addition, it is very efficient when combined with Nanite**.**

Nanite is the new geometry virtualisation system, which is automatically divided into clusters that function as dynamic LODs (Level of Details) and are loaded with the required levels of detail according to the viewing distance/occlusion without affecting hardware

performance, neither in the number of draw calls, nor in memory load associated with the number of polygons by loading only the required geometry sections according to the camera view. In theory, an almost infinite number of polygons can be handled, which opens up a new perspective in the creation of digital environments, as we can move billions of polygons on screen fluidly with super-efficient geometry management.
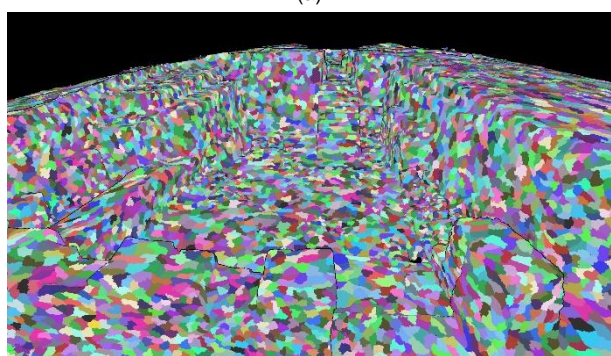
A hyper-realistic lighting system of immediate calculation, without tricks or pre-calculations, together with efficient management of geometry seems to be the
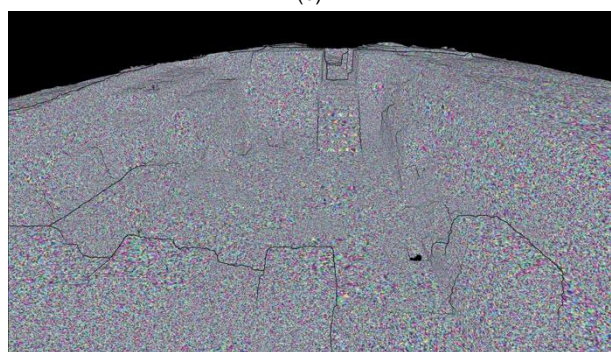
closest thing to creating a true virtual world without limitations. But we will now explore its pros and cons and how it benefits us to apply it to virtual heritage reconstruction projects (Fig. 13).
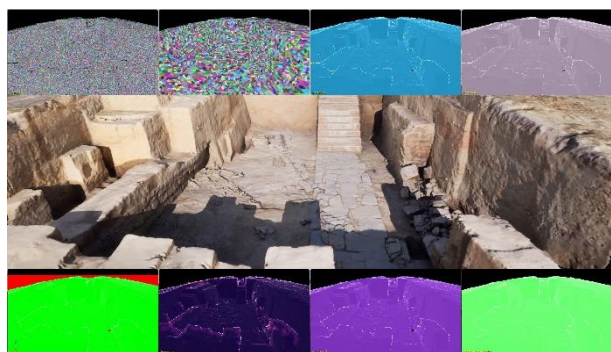
(a)

(b)

(c)

Figure 13: a) Geometry virtualisation preview modes in Nanite (UE5); b) Geometry virtualisation with dynamic clusters in Nanite (UE5); and c) Geometry virtualisation with dynamic triangles in Nanite (UE5), all based on the photogrammetric model.

With the incorporation of Nanite, the optimisation of models and the creation of LODs becomes completely unnecessary, as models of any size can be imported without affecting performance due to the virtualisation of the geometry. In this sense, in the tests carried out with the photogrammetry of the Casas del Turuñuelo site, the performance with Unreal v. 4.27 was optimal, even with 3.6 million polygons. This is due to the fact that the hardware used, an Nvidia RTX 3080ti graphics card, has sufficient capacity to handle that amount of geometry; however, with lower-performance graphics cards we would have performance problems with large geometries when we are talking about several million polygons. In UE5, with the geometry converted to Nanite, the limits disappear. In our tests, when creating a matrix of 36 copies of the same photogrammetry (130 million

polygons) the performance is not affected at all. Therefore, we could still multiply this figure by 10 and the performance would remain the same, which was an impossible task with previous versions of Unreal Engine and with most 3D software (Fig. 14).

Figure 14: Real-time photogrammetry walkthrough in Unreal Engine 5.03. To see the result in motion, visit the following address for a video:
https://www.youtube.com/watch?v=NCOeqVTyU_g

The advantages of using Unreal 5 lead us to think about the possibility of creating ultra-detailed photogrammetries in the future with which to work without the need to optimise the models or create normal textures to replace the detail lost in the simplified models. Although it will be possible to do so, this factor should not condition our way of working, making us abandon our usual workflow, as the trade-offs are obvious.

Firstly, we must bear in mind that photogrammetry is still a necessary tool for working in other 3D editors with lower performance or its use in platforms such as Sketchfab, to which we can add the need for hard disk space to store photogrammetric models generated without any size limitation. In these circumstances it may be advisable to work with larger polygon quantities in order to take advantage of all the detail provided by the photogrammetry software we use, seeking a balance according to the final use of the model. As an example, and in very general terms, sometimes we will not appreciate too much visual difference between a model with 20 million polygons and another one with between 5 and 10 million, although the difference in the size of the disk file will be very evident. Therefore, the most advisable thing to do is to look for an optimal point depending on the uses we give to our photogrammetry, including possible AR/VR applications, where we will unavoidably need a highly optimised model.

Heritage reconstruction projects rarely compare to the huge, super-detailed open worlds we see in video games. The most extensive current case in the heritage sector is the creation of the real-time model of Rome by Faber Courtial, where the Nanite package management system has been essential to create an entire city with enough detail to be navigable in any of its locations, and for which a specific software has been created in order to load the huge amount of data required. Another recurring scenario is the creation of large terrains with natural environments, but these have their own specific creation method with a high level of optimisation from previous versions of Unreal Engine and work very efficiently, so Nanite will be applied more to large environments with a huge amount of geometry, as is the case of Epic Games'

demo project, "Valley of the Ancient", creating a very complex landscape. Generally speaking, Nanite will be most useful in large, highly detailed building complexes and, if necessary, in the creation of large photogrammetric models that can be made up of many partial models, such as an entire city assembled in smaller parts to make it more manageable.

In turn, the light tests carried out with Lumen on the virtual model of Casas del Turuñuelo have shown the great advantages of this system over standard ray tracing. Both the performance of the hardware has improved notably by offering a more direct and robust calculation, as well as the quality of the lighting, as we now have a bounced light in interiors that is much more realistic and closer to the calculation of offline rendering engines, with more power in dark environments and with better interior/exterior transitions (Fig. 15).

One factor to take into account for the implementation of Lumen and Nanite in UE 5 is that its use is oriented to high-performance PC systems and next-generation game consoles, so we must take into account the requirements of the GPU to be able to use this technology. It is for this reason that its implementation in VR is not being developed at the moment, due to the high resolution demands of dual-screen VR viewers and the high framerates required for a smooth experience. Thus, workflows based on less performance-demanding lighting and geometry management systems need to be available in future versions of Unreal Engine to solve XR/AR and VR-oriented projects until the technology opens up these capabilities to lower-cost devices.

Pending the release of the final version, some incompatibilities with certain types of materials and inaccuracies of both systems remain to be resolved for the time being. It is therefore not advisable to use the early access version in final production in order to avoid these inconsistencies. However, it is an excellent proving ground for testing its new features and assessing the possibilities in the development and projection of the new versions of our project.

In the course of reviewing this paper, the project has been migrated and adapted to the final release of Unreal Engine v. 5.0.2 and has shown a huge improvement in the quality of Lumen´s light calculation and its enhanced real-time performance.

7. Conclusions

The virtual reconstruction of an archaeological site is a never-ending task, as working with a single working hypothesis is a practically unattainable reality. As such, history is a discipline under constant construction, so the future is always open to the reception of new data or interpretations derived from new research work that will make us rethink the previously validated solution. This situation becomes even more evident when the virtual reconstruction is carried out in parallel to the archaeological excavation, in such a way that we will observe how the virtual model grows at the same pace as the excavated areas grow, thus incorporating new spaces, which will force us to revise those parts of the model that we previously thought we had resolved. It is therefore essential to create a robust and coherent working system that facilitates the task of introducing modifications and creating new parts, taking into account the criteria of updating and reversibility of virtual reconstruction.

The working method used to develop the virtual reconstruction of Casas del Turuñuelo was designed to take advantage of all the benefits offered by the real-time rendering engine, taking into account the immediacy of the results, the possibilities of interaction with the 3D environment and the speed of calculation of images and video for scientific dissemination and social dissemination. This has allowed us to achieve a degree of visual realism that can come very close or even equal to an offline rendering system, which allows us today to have a work base oriented to incorporate new technological solutions that will help us to create immersive experiences in the future.

Figure 15: Lighting test with Lumen of room H100 with effects, in UE 5.

In the current state of the art, we are aware of the complexity of implementing the real-time rendering engine as a tool for the reconstruction of archaeological sites. Firstly, because it is a rapidly changing technological environment that evolves very quickly, which requires constant training, while at the same time taking advantage of the benefits offered by the improvements of successive versions. Secondly, the need for state-of-the-art hardware, in terms of GPUs, requires an investment to acquire hardware with sufficient power to handle the requirements of the project.

Despite all this, we see enormous advantages in the application of the real-time rendering system with Unreal Engine to the field of archaeological heritage, taking advantage of the enormous possibilities that the new version 5 offers us. These include the possibility of working with practically infinite geometry, something that no other 3D visualisation software can compete with at the moment, as well as the possibility of achieving real-time quality lighting, at a level similar to an offline system but much more efficient.

The result is a high-quality virtual reconstruction model that opens up a wide range of possibilities (Fig. 16). At the research level, the graphic quality provided by this technology gives us a final model suitable for the execution of structural and architectural analyses, as we can see in the study of the site of Casas del Turuñuelo. However, the field of dissemination is where the best performance can be obtained from the implementation of real-time ray tracing technology, by opening new horizons in disciplines such as heritage education or tourism (Rivero & Feliu, 2017).

In this sense, having a final image of what an archaeological site would have looked like, in this particular case the building at Casas del Turuñuelo, allows us to bring our research closer to the community by translating the archaeological remains into a language that can be understood by society at large. The pace of dissemination will increase with the future development of technology, which promises great advances in the coming years. The incorporation

Figure 16: Walkthrough in real-time through the model in Unreal Engine v. 5.03. To see the result in motion, visit the following address for a video: https://www.youtube.com/watch?v=TCosJY9E9Vo.

of technologies such as XR/AR/VR makes this project a very powerful tool to introduce the concept of gamification, taking advantage of all the potential that software oriented to the creation of video games can offer.

With this study, we aim to contribute to the fulfilment and dissemination of some of the main objectives defended in the Seville Principles (ICOMOS, 2017. We seek to open the way to the implementation of new digital methods and techniques that favour both research and dissemination, through the presentation of results that contribute to a better and greater understanding of archaeological science.

Acknowledgements

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