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BEYOND THE WALLS: THE DESIGN AND DEVELOPMENT OF THE PETRALONA CAVE VIRTUAL MUSEUM UTILISING 3D TECHNOLOGIES

MÁS ALLÁ DE LOS MUROS: EL DISEÑO Y DESARROLLO DEL MUSEO VIRTUAL DE LA CUEVA DE PETRALONA UTILIZANDO TECNOLOGÍAS 3D

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Highlights:

- The Petralona Cave is significant due to the discovery of Greece's oldest human remains, an extensive collection of fossilised animal bones, and numerous Palaeolithic tools.
- The Petralona Cave Virtual Museum was designed and developed to meet the diverse needs and interests of visitors by utilising cutting-edge digital technologies.
- The Virtual Museum is expected to enhance the visibility of the Petralona site, contributing to the dissemination of knowledge about this important cultural heritage asset.

Abstract:

The Petralona Cave, which local inhabitants discovered by chance in 1959, is a remarkable natural and cultural landmark close to the village of Petralona, in the Chalkidiki peninsula of Greece. The site has gained global recognition for the discovery of a remarkably well-preserved Palaeolithic human skull, unearthed in 1960; it also holds archaeological and palaeontological significance. In this paper, the researchers introduce the Petralona Cave Virtual Museum: an innovative project whose mission is to increase public awareness and comprehension of the site. Our approach goes beyond mere replication of the physical museum located close to the cave; instead, the objective is to create an independent and comprehensive experience that is accessible to all visitors, irrespective of their ability to visit the site in person. Our methodology involved the documentation of the site and its history, analysis of user requirements, development of use cases to steer the design process, as well as architectural designs creation, itineraries and findings digitisation, and architectural structure finalisation. The Virtual Museum provides a well-organised frame structure that serves as an efficient gateway to the content, making navigation easy for visitors. Thanks to various presentation methods, including videos, high-quality images, interactive maps, animated content, interactive 3D models, plus searchable item libraries, among others, users are empowered to create a highly personalised navigation plan; thus the Virtual Museum experience is comparable to visiting the physical museum or cultural site. Cutting-edge digitisation techniques were employed to create highly detailed 3D models of the site. The Petralona Cave Virtual Museum is expected to offer an immersive experience, engaging diverse audiences; the interactive and educational exploration provides highly innovative access to archaeological knowledge. The visibility of the Petralona site is amplified and there is a significant contribution to knowledge dissemination about this important cultural heritage site.

Keywords: virtual museum; Palaeolithic archaeology; 3D modelling; cultural heritage; digitisation

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Resumen:

La cueva de Petralona, descubierta casualmente en 1959 por habitantes locales, es un hito natural y cultural notable ubicado muy cerca del pueblo de Petralona, en la península de Calcídica en Grecia. El sitio ha ganado reconocimiento mundial por el descubrimiento de un cráneo humano paleolítico notablemente bien conservado, desenterrado en 1960; también tiene importancia arqueológica y paleontológica. En este artículo, presentamos el Museo Virtual de la Cueva de Petralona, un proyecto innovador con la misión de aumentar la conciencia pública y la comprensión del sitio. Nuestro enfoque va más allá de una mera réplica del museo físico ubicado cerca de la cueva: el objetivo es crear una experiencia independiente e integral, que sea accesible para todos los visitantes, independientemente de su capacidad de visitar el sitio en persona. Nuestra metodología involucró la documentación del sitio y su historia, el análisis de los requisitos de los usuarios, el desarrollo de casos de uso para guiar el proceso de diseño, la creación de diseños arquitectónicos, la digitalización de itinerarios y hallazgos, así como la finalización de la estructura arquitectónica. El Museo Virtual proporciona un marco bien organizado que sirve como de puerta de entrada eficiente al contenido: los visitantes pueden navegar con facilidad. Se incorporan varios métodos de presentación, incluyendo vídeos, imágenes de alta calidad, mapas interactivos, contenido animado, modelos 3D interactivos, además de bibliotecas de elementos con capacidad de búsqueda y más; gracias a todo ello, los usuarios pueden crear un plan de navegación altamente personalizado. En última instancia, se proporciona una experiencia de Museo Virtual comparable a visitar el museo físico o sitio cultural. Se emplearon técnicas de digitalización de vanguardia para crear modelos 3D muy detallados del sitio. El Museo Virtual de la Cueva de Petralona se espera que ofrezca una experiencia inmersiva que atraiga a audiencias diversas; la exploración es interactiva y de alto valor educativo, revolucionando el acceso al conocimiento arqueológico. En última instancia, se amplifica la visibilidad del sitio de Petralona y se contribuye significativamente a la difusión del conocimiento sobre este importante sitio del patrimonio cultural.

Palabras clave: museo virtual; arqueología paleolítica; modelado 3D; patrimonio cultural; digitalización

1. Introduction

The Petralona Cave, serendipitously discovered in 1959 by local inhabitants, is a notable natural and cultural landmark situated in the western foothills of Mount Katsika, proximate to the village of Petralona, within the Chalkidiki peninsula, northern Greece (Figure 1). It is a site of great importance and unique value due to the discovery of the oldest human remains found so far in Greece and one of the oldest and one of the best-preserved skulls in Europe, unequivocally constituting a significant component in the study of human evolution (Harvati, 2009; 2022; Koufos & Tsoukala, 2007; Stringer, 1974; 1980; Stringer, Howell, & Melentis, 1979). Additionally, the cave boasts an extensive collection of fossilised animal bones, which have been referred to more than fifty species of amphibians, reptiles, birds and mammals. Formed approximately a million years ago, the cave spans an area of roughly 10400 m^2, encompassing an array of chambers, soaring ceilings, and lagoons, replete with an abundance of stalactites, stalagmites, draperies, columns, and other formations.

Figure 1: The Petralona Cave is situated in the western foothills of Mount Katsika, proximate to the village of Petralona, within the Chalkidiki peninsula, Greece: (a) map of Greece indicating the location of the cave (red dot); (b) aerial view of the village Petralona and Mount Katsika; (c) view of the cave interior; (d) the current artificial entrance of the cave.

The Museum of Petralona Cave is located just a few metres from the cave entrance and is the sole institution of its kind in Greece. Its exhibition is dedicated to showcasing the cave's formation and presenting the palaeontological and archaeological discoveries uncovered within, dating back to deep prehistory. As a result of these captivating features, the Petralona Cave and Museum have become a renowned tourist attraction, welcoming over 50000 visitors annually.

However, the cave's limited accessibility for wheelchair users and visitors with mobility impairments, due to its narrow passageways and stairs, means only a restricted area is accessible. Moreover, the guided tour covers only a small portion of the cave, preventing many impressive cave formations from being visible to the public. To ensure visitor safety and prevent overcrowding in the cave's microenvironment, only small groups are allowed on the tour. Furthermore, the tour is brief, especially during peak season, so visitors may not have sufficient time to appreciate the cave's physical beauty. The establishment of a virtual museum could partially mitigate these limitations.

1.1. Geological and archaeological background

The Petralona cave was formed within an Upper Jurassic, thick-bedded limestone, deposited in a marine environment approximately 120–100 million years ago. It features a horizontal development and spans an impressive total area of around 10400 m^2. Much of the cave's extent remains inadequately explored and documented, leaving ample opportunity for future investigation and discovery. It extends in two main directions, namely NW-SE and NE-SW. Its intricate layout, characterised by large halls adorned with stunning stalactite and stalagmite formations, is believed to have taken shape during the Early Pleistocene Epoch. During its nascent stages, and for a long period thereafter, it lacked an entrance or communication with the external environment. Eventually, a fissure in the roof of one of its chambers created an opening. The occurrence of a large talus at the cave's central area attests to the presence of this entrance, through which sediments were transported and deposited within the cave over time. This entrance also allowed carnivores, like cave bears (*Ursus deningeri*) and spotted hyenas (*Crocuta crocuta praespelaea*) to use the cave as a refuge during winter hibernation, or a den, respectively. Herbivore fossils are also common in the cave deposits, ending there accidentally, or carried there by the carnivores as prey. The cave's fossil content has been published in a series of papers by several authors (Baryshnikov & Tsoukala, 2010; Crégut-Bonnoure & Tsoukala, 2005; Fortelius & Poulianos, 1979; Kretzoi, 1977; Kretzoi & Poulianos, 1981; Kurtén, 1983; Kurtén & Poulianos, 1977; 1981; Rabeder & Tsoukala, 1990; Sickenberg, 1964; 1971; Tsoukala, 1989; Tsoukala & Guérin, 2016).

Of particular interest is the Petralona human skull (Fig. 2), allegedly found in the "Mausoleum chamber", and considered the most significant palaeoanthropological find in Greece. It represents one of the most well-preserved and complete skulls of *Homo heidelbergensis*, characterised by a relatively elongated and robust cranial vault with a large cranial capacity (approximately 1200 cm^3), prominent brow ridges, large ocular orbits, a broad face, and a strong dentition (Aidonis et al., 2023; Harvati, 2009; Koufos & Tsoukala, 2007; Stringer, 1974; 1980; Stringer, Howell, & Melentis, 1979,). Specimens with comparable morphology have been found in other parts of the world, such as in France (Arago cave), Zambia (Broken Hill / Kabwe cave), and Ethiopia (Bodo). The Petralona Cave's findings are of particular importance for the investigation of one of the earliest human occupations of Europe since it is located at the threshold of the European continent, on one of the possible routes of dispersal of early humans (Darlas, 2014; Harvati, Panagopoulou, & Runnels, 2009).

According to unpublished chronologic data, the human presence in the cave initially occurred during the early Middle Pleistocene, with evidence of their activity found within the layers of the thick talus deposit (Trench B), interspersed with palaeontological and archaeological remnants (see also Darlas, 2014). Lithic tools have been found in context with fossilised, fragmented herbivore bones (fallow deer, horse, wild goat), some of them bearing cut marks indicating butchery activities (research in progress).

Figure 2: The Petralona human skull after the first preparation efforts (Kanellis & Marinos, 1969. Fig. 2, modified).

The continuous accumulation of sediments ultimately led to the closing of the entrance, resulting in the isolation of the cave and, consequently, the preservation of its palaeontological and archaeological content. Nowadays, visitors enter the cave through an artificial tunnel.

1.2. The under-representation of the Palaeolithic archaeology in Greek museums

The Palaeolithic period, spanning from the very beginning of the human archaeological record to about 10000 years ago, is a crucial period in human history marked by the early stages of human evolution and the development of stone tools. Despite its importance, this era is often underrepresented or absent in museum exhibitions in Greece. While there are a few examples of museums in Greece that present Palaeolithic artefacts and finds in their collections, none are solely devoted to the presentation of the Palaeolithic period. This lack of attention to the Palaeolithic period in Greek museums means that there is a significant gap in public knowledge and understanding of this important era.

However, the Petralona Cave Virtual Museum is seeking to change this by being the first museum in Greece to be entirely devoted to the Palaeolithic period, as is also the case for the Petralona physical museum. This museum

not only presents the findings of the Petralona Cave, one of the earliest archaeological sites in Greece and Europe but also aims to educate visitors about the significance of the Palaeolithic period in human history. The museum features a great number of Lower Palaeolithic lithic artefacts, knapped by groups who inhabited the cave during the Middle Pleistocene period. These findings are of particular importance for the investigation of the early human occupations of Europe, as the Petralona Cave is located on one of the possible routes followed by early humans during their early dispersals to the European continent.

1.3. Aim

The development of the Petralona Cave Virtual Museum is part of the Cave3 Project, which utilises state-of-the-art digital technologies for developing innovative mechanisms to widely disseminate the natural and cultural assets of the Petralona Cave and the Petralona Museum, and also to provide an interactive experience to the visitors. The project focuses also on satisfying the needs of visitors with disabilities, a group with special requirements that should be always considered in the framework of the "culture-for-all" and "tourism-for-all" concepts.

These state-of-the-art 3D technologies can revolutionise the way visitors engage with the cave and museum, providing a means of education and entertainment for both the general public and scientists. As an interpretation centre, the Cave3 Project offers a unique and captivating way to discover the cave, utilising state-of-the-art experiential storytelling technology to create a sense of wonder and mystery.

The development of the Petralona Cave Virtual Museum was a key component of the Cave3 Project. It does not perform as a digital substitute for the physical museum, instead, it acts independently and complementary to it. The Petralona Cave Virtual Museum project aimed to: a) enrich the cave and museum physical visit by offering different storytelling experiences; b) create more opportunities for visitors to develop independent experiences; c) prolong the visitor experience after they have left the physical space; and d) provide worldwide publicity. The present paper presents the design and development of the Petralona Cave Virtual Museum.

1.4. Research objectives

Petralona Cave is a cultural heritage asset. Interpretation and presentation are considered to be critical in the protection of cultural heritage. Both of them are essential components of heritage conservation and a means of enhancing public appreciation and understanding of cultural heritage sites. According to ICOMOS (2008, 4) Interpretation "refers to the full range of potential activities intended to heighten public awareness and enhance understanding of cultural heritage site" and Presentation "denotes the carefully planned communication of interpretive content through the arrangement of interpretive information, physical access, and interpretive infrastructure at a cultural heritage site". The objectives set for the design and development of the Petralona Cave Virtual Museum are in accordance with the principles established by the ICOMOS charter (2008), upon which Interpretation and Presentation should be based. The objectives set are to:

- Create a holistic virtual museum and educational experience.
- Facilitate understanding and appreciation of the site, communicate its importance and stimulate further interest, learning, experience and exploration considering all aspects of the site's significance and values.
- Allow free and equal access to all public types through careful, documented accepted scientific methods.
- Develop appropriate technical guidelines ensuring ease of access in the Petralona Cave Virtual Museum.
- Contribute to the sustainable conservation of the cultural heritage site, through promoting public understanding of, and participation in, ongoing conservation efforts, regularly reviewing its interpretive contents.
- Raise the awareness and increase public sensitivity about the protection of caves and their ecosystems.
- Disseminate the little-known archaeology of the Palaeolithic period to the public.
- Offer new possibilities for interaction and manipulation of the heritage asset.
- Take into consideration the surrounding landscape, natural environment and geographical setting, since they are integral parts of a site's cultural significance.

2. Methodology

To ensure a seamless visitor experience, we applied a five-step methodology that included: i) thorough documentation of the site and its history; ii) detailed analysis of user requirements; iii) development of use cases to guide the design process; iv) creation of architectural designs and digitisation of itineraries and findings; and v) creation of the final architectural structure. By carefully following these steps, we were able to ensure that the visitor experience was well-planned, intuitive, and engaging. Each step was informed by the previous one, and together they formed a cohesive and comprehensive approach to designing the Virtual Museum. By placing an emphasis on user needs and expectations, we were able to create a digital experience that is accessible to all visitors, regardless of their background or expertise.

2.1. Documentation

As a first step, we conducted archival research by gathering and recording written and visual content, as well as digitised material that could be useful for the project. Additionally, we explored possible speleological or other equipment that may have been used during the early research phase.

2.2. User requirement analysis

To gather information about the end-user's needs, we structured a comprehensive online questionnaire using Google Forms. The survey was conducted between 24 July and 21 December 2020 and was self-administered by the participants, ensuring anonymity. The questionnaire was based on five key thematic groups:

"Demographic Information". This section captures essential demographic details of the participants such as age, gender, education level.

"General Preferences". This section covers general preferences of users when engaging with museums, covering aspects such as frequency of museum visits whether physical or virtual, and the reasons of visiting a museum.

"User Experience and Design". This part investigates user interaction and design preferences. It examines the ease of navigation, visual appeal, functionality, and overall user-friendliness of the virtual museum interface.

"Content" focused on the specifics of the material presented in the virtual museum. It might delve into the types of exhibits preferred, topics of interest, depth of information desired, and the effectiveness of conveying knowledge through different content formats (e.g., videos, texts, interactive displays).

"Accessibility and Inclusivity". This section is dedicated to ensuring that the virtual museum is accessible to all individuals, regardless of abilities or limitations. It aims to assess the inclusivity of the design, such as considering accessibility features for users with disabilities, multi-language support, or other means to ensure broader access.

In total, 13 standardised and concise closed-ended questions were included. Participants were presented with multiple options to choose from, based on their preferences.

2.3. Use case

We developed a storyboard that was guided by the objectives we had established and the needs of end-users, as revealed by our questionnaire survey. The result was the creation of two distinct use cases: Introduction and Context, and Virtual Tour of the Petralona Cave.

To ensure a user-friendly experience, we designed the homepage of the Petralona Cave Virtual Museum to be inviting and informative. As soon as visitors land on the homepage, they are provided with general information about the site. We also added two easy-to-use navigational options: Discover the Cave and Virtual Tour. The Discover the Cave option is tailored towards those who want to delve deeper into the fascinating history and research concerning the Petralona Cave. It offers visitors useful and interesting information about the cave, including the numerous groundbreaking discoveries made from the early 1960s until the present day. The Virtual Tour option, on the other hand, is a guided exploration inside the cave that is meant to offer visitors a unique and immersive experience. Our Virtual Tour provides visitors with a comprehensive look at the Petralona cave, focusing on spots of specific geological, archaeological, or palaeoanthropological interest. We have incorporated cutting-edge 3D technology that enables visitors to experience the cave's interior in a manner that is both engaging and educational. Visitors are able to navigate through the cave's passages, discovering its many wonders along the way.

2.4. Digitisation processes

After establishing the reference storyboard, the process of modelling the pre-defined environments began. Technical specifications were determined through a comprehensive investigation of the available technological infrastructures. A critical analysis of each possibility and a cost-benefit assessment was conducted. In addition, functional requirements were established based on detailed documentation of the individual subsystems' functional specifications in the digital platform.

The modelling process was executed with attention to detail, so as to ensure that the environments created were faithful to the physical space and reflective of the immersive experience we aimed to provide. Our team utilised the latest digital tools and techniques to ensure that the resulting virtual environment was both technically robust and visually appealing (Table 1). Additionally, we performed frequent testing and debugging to guarantee a seamless and enjoyable user experience.

To 3D scan the Petralona Cave and create a coloured point cloud of its geometry, a FARO scanner model Focus 3D S120 was used. In total, 140 scans were carried out with varying scanner resolutions. To achieve a similar point-cloud density overall inside the cave, a scan resolution of 47 million points per scan was used in narrow passages and a scan resolution of 174 million points per scan in larger rooms. To realistically reproduce the actual texture of the Petralona Cave, but also to improve the geometry in blind spots of the 3D scanner, ground shots were taken with a Hasselblad X1D II medium format digital camera, with a 50 MP sensor, 30 mm lens (equivalent to 24 mm in a full-frame camera). In total, more than 6000 shots were taken with the medium-format camera to fully cover the Petralona Cave. To optimally capture the entrance of the Petralona Cave, as well as for 3D rendering purposes of the surface area above it, a professional unmanned aerial vehicle, namely DJI Phantom 4 RTK model, was used. The UAV was equipped with a 20 MP camera.

A collection of findings was also digitised in very high quality. The selection of findings was based on their scientific importance, as well as their physical condition. The 3D scanning process followed a typical four-step procedure (Figure 3), namely: the generation of the point cloud with a 3D scanner, noise clearance, inter-alignment of point clouds, mesh creation, and processing through special algorithms and commands for triangular grid (wireframe) creation, as well as texturing (i.e., natural colouring of digital copies).

The process of digitisation combined conservation methodologies with management strategies, photographic methods, 3D scanning techniques using the ARTEC EVA 3D Scanner, and the utilisation of unmanned aerial systems (Stylianidis, Georgopoulos, & Remondino, 2016).

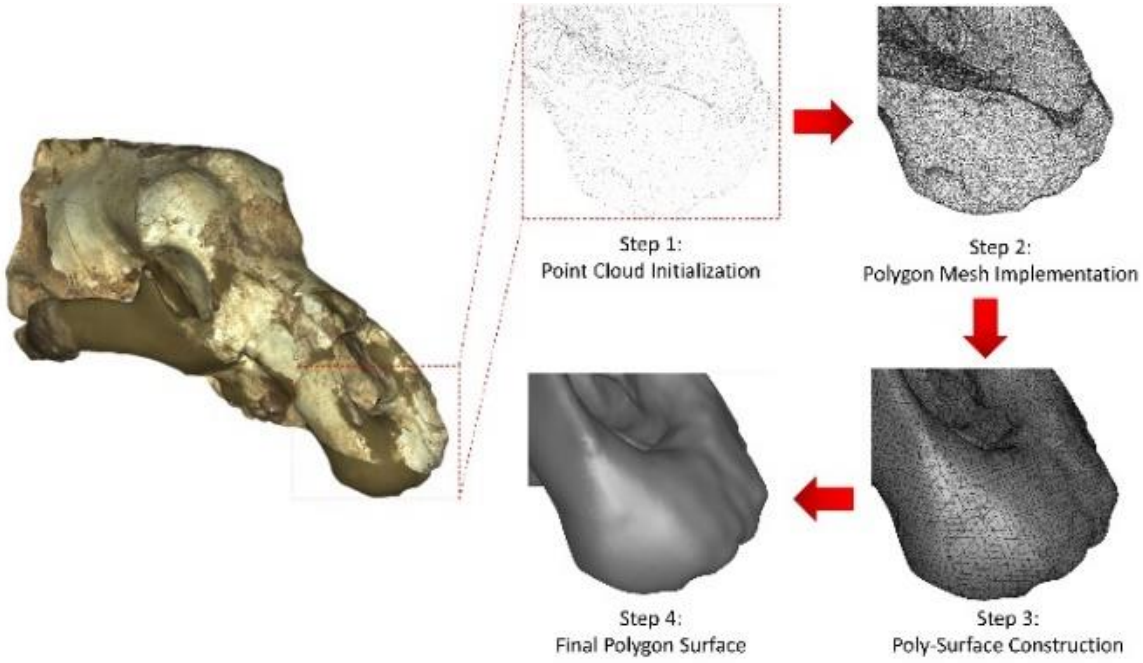


Figure 3: Four-step 3D scanning procedure. An example of a fossil bear skull.

Table 1: Specifications of the used equipment.

Equipment	***ARTEC***	***FARO***	***Hasselbland***	***DJI***
Model	EVA	FOCUS 3D S120	X1 D II	Phantom 4 RTK
Technology	White Light	Laser	Digital Camera	UAV
Type	Handheld	Terrestrial	Handheld	Drone
Accuracy / Resolution	0.1 – 0.5 mm	2.0 – 4.0 mm	8272 x 6200	5472 x 3648
Texture	YES	YES	YES	YES
Tex. Resolution	1.3 mp	70 mp	50 mp	20 mp
Frame Rate	60 fps	-	25 fps	60 fps
Weight	0.90 kg	5.00 kg	0.76 kg	1.31 kg
Main Export	STL, OBJ	E57, XYZ	JPEG, TIFF	JPEG, MP4
Working Distance	0.4 m – 1 m	0.6 m – 120 m	Dep. On Lens	0.7 m – 30 m

2.5. Creation of the Petralona Cave Virtual Museum architectural structure

The primary objective of the Virtual Museum's architectural design was to create an environment where diverse types of information and presentation styles could coexist as separate entities, while also forming an interconnected whole through multiple hyper-textual connections and associations. To enhance the linear narrative of the video presentation showcasing the cave's environment on the Virtual Tour section of the website, interactive stops have been incorporated. These stops enable the virtual visitors to pause the presentation temporarily and either focus on specific points of interest or navigate to other relevant sections of the website structure, such as the architectural plan of the cave or the detailed textual presentation in the Discover the Cave section. This approach empowers users to deepen their understanding and knowledge of the cave's history and significance in various ways. The experience interchanges from a more passive and immersive video presentation to a more active, constructive, and personalised exploration of the provided multimedia items and information. This practice aligns with the principles of constructivist learning theories, harnessing their benefits. Ultimately, the clearly delineated website sections aim to group similar types of information together, enabling users to navigate among them easily and with clarity.

3. Results

Following our methodological steps, we developed the Petralona Cave Virtual Museum that offers a structured framework, which acts as an efficient entry point to its content and facilitating seamless navigation for visitors. By integrating diverse presentation formats such as videos, high-resolution images, interactive maps, animated elements, 3D models, searchable item libraries, and more, it enables users to tailor their own navigation

plan, resulting in a Virtual Museum experience comparable to an in-person visit to the physical museum and/or the cave. Furthermore, advanced digitisation techniques were employed to create intricate 3D models of the site.

3.1. Documentation

Our archival research comprised a comprehensive collection of written and visual content, including scientific articles, books, documents, manuscripts, records, and photographs (Fig. 4). We sourced these materials from several reputable institutions, including public libraries, the Hellenic Speleological Society, and the Geology–Palaeontology–Palaeoanthropology Museum of the School of Geology at the Aristotle University of Thessaloniki. To supplement this, we also gathered archival material from the local community, which consisted mainly of photographs and old speleological equipment. The inhabitants of Petralona village, who were actively involved in the exploration of the cave, were a valuable source of information. In addition, we carefully recorded and analysed intriguing details that we obtained during our interactions with local citizens regarding the discovery of the cave and the skull, as well as the investigations that have been conducted in Petralona Cave over the past several decades.

Figure 4: A part of the archival collection.

3.2. User requirement

A representative sample of 117 individuals with varying ages, gender, and educational backgrounds participated in the survey.

Based on the questionnaire responses, it appears that the majority of participants (63.2%) visit a museum once a year for both knowledge and entertainment, primarily drawn to the displayed objects and their presentation method.

Interestingly, the majority of participants (47.4%) reported that they would have visited a virtual museum much more often than a physical one (once a month). Furthermore, the 89.5% of the participants believe that visiting the virtual museum would have motivated them to visit the physical museum and/or the archaeological site.

They suggested that incorporating new technologies would be crucial and envisioned a scenario where visitors could have access through their computers or mobile devices. They consider the interactivity within the virtual museum (e.g., being able to interact with artefacts, participate in virtual tours, etc.) to be very important, along with the user-friendly interface and easy navigation within the virtual museum, both of which are rated at 84.2%.

The participants believed that immersive virtual tours and 3D representations of findings would significantly enhance their educational experience, providing an effective means to deepen their understanding of the subject matter. Moreover, the participants expressed a keen interest in storytelling, considering it an essential aspect of creating a captivating and intuitive visitor experience. They believed that such an experience would enable them to better comprehend and engage with the museum's content. However, the participants appeared to be less enthusiastic about lengthy texts, possibly owing to their past experiences with overlong texts found in museums. They favoured shorter yet comprehensive texts that could effectively disseminate knowledge. Therefore, incorporating concise but informative texts would be crucial to effectively communicate with visitors.

It is noteworthy that nearly a quarter (26.3%) of the participants mentioned specific accessibility needs or preferences, with their input implying that the virtual museum design team should take these into account.

3.3. Use case: The narrative

The homepage of the Virtual Museum provides a well-organised frame structure that serves as an efficient gateway to the Museum's content, allowing visitors to navigate with ease (Fig. 5). The introductory preview text on the homepage provides fundamental information about the cave's location and its significance, capturing the audience's attention and inviting them to learn more by clicking on the "find out more" button (Fig. 6). The ensuing window includes the above-mentioned introductory text along with the captivating high-resolution aerial footage of the site and its surroundings. Additionally, as the visitor scrolls down the homepage, informative hints highlighting the most critical aspects of the site are presented.

The homepage also features a language selection option that allows visitors to choose between Greek and English. In the top right corner of the page, a simple and clean menu icon is located. Hovering over the menu icon provides access to eight options for further navigation, including (i) Virtual tour, (ii) Map of the cave, (iii) Discover the cave, (iv) Asking the experts, (v) Media and Resources, (vi) Visit the cave, (vii) Credits, and (viii) 3D scan of the cave (Figs. 7 and 8).

Figure 5: Snapshot of the Petralona Cave Virtual Museum homepage.

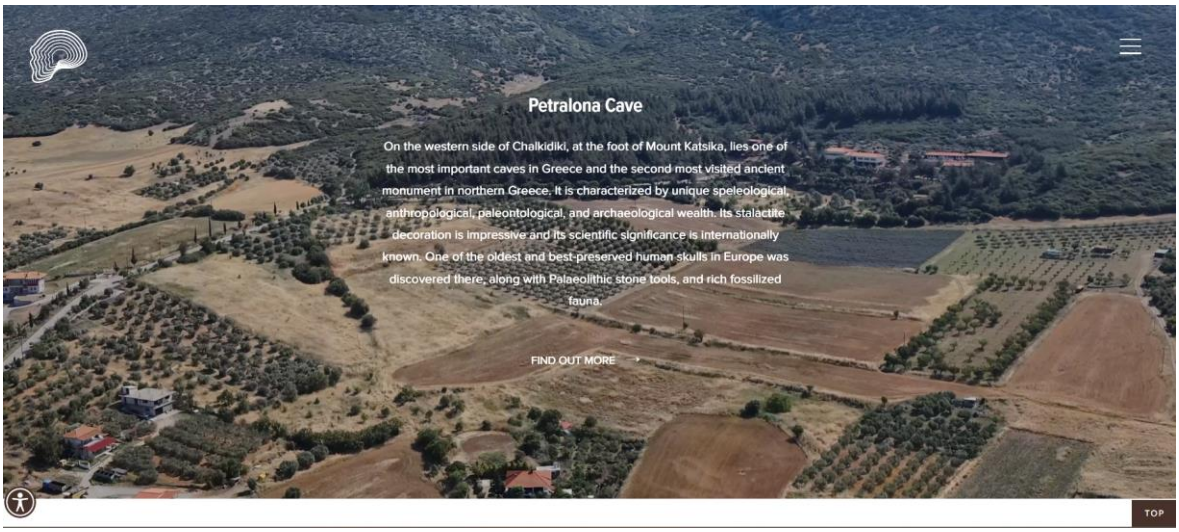


Figure 6: Snapshot of the introductory preview text on the homepage providing fundamental information about the cave's location and its significance.

Figure 7: Snapshot of the menu sidebar including eight options for further navigation.

Figure 8: Snapshot of the Map of the cave. The visitor can choose among the seven suggested stops gathering a wealth of information about the archaeological, geological, and palaeoanthropological discoveries made at the site, as well as the opportunity to interact with 3D renderings of the fossil bones and the human skull found in the cave.

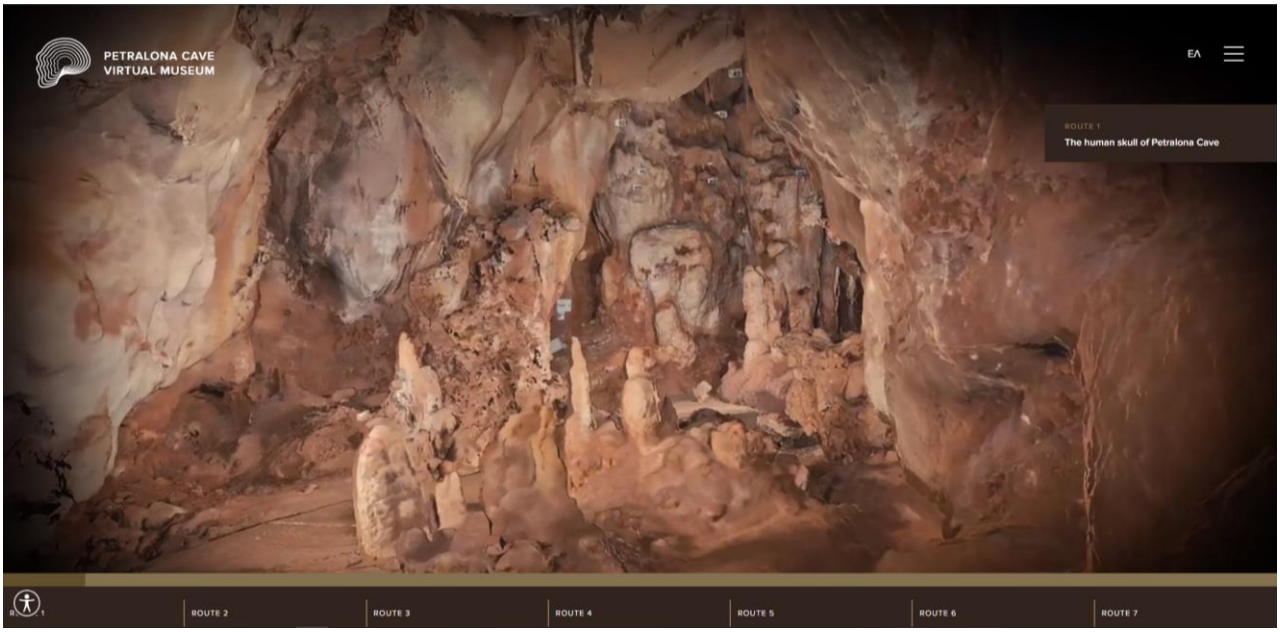


Figure 9: Snapshot of the Route 1 of the 'Virtual tour' presenting the place where the Petralona human skull was found.

The 'Virtual tour' has been designed in order to provide an engaging and immersive experience for online visitors (Figure 9). It comprises seven points of interest strategically located both on and off the main path that visitors follow during a physical visit. Each stop presents a wealth of information about the archaeological, geological, and palaeoanthropological discoveries made at the site, as well as the opportunity to interact with 3D renderings of the fossil bones and human skull found in the cave. By offering this rich array of supplementary material, the virtual tour offers a unique perspective and a chance to explore the site in a way that would not be possible during a physical visit alone.

The "Discover the cave" option offers visitors an immersive experience by providing comprehensive information through concise written descriptions and visually stunning multimedia resources such as photographs, videos, and 3D digital models of the human skull and various fossilised animal bones, as well as archival materials. This interactive feature offers a fascinating account of the discovery of the Petralona Cave and its fossil human skull, as well as an overview of the extensive research that has been conducted on this site since the 1960s. Additionally, the visitor can be informed about the different species of animals that used the cave as shelter or ended there as carnivores' or humans' prey and the human groups that inhabited the cave during the Middle Pleistocene. A sub-section is devoted to the formation of the Petralona Cave.

The 'Asking the experts' feature presents an engaging series of videos where specialists in archaeology and palaeontology respond to fifteen commonly asked questions about prehistoric humans and fossil faunas. This interactive tool was specifically designed to accommodate museum visitors, particularly school children, seeking expert knowledge on these subjects.

The 'Visit the Cave' option offers practical information regarding the precise location of the cave and detailed directions on how to get there.

The 'Media & Resources' option compiles all multimedia materials, along with a curated bibliography related to the Petralona Cave, providing visitors with a wealth of information.

3.4. Digitisation of itineraries and findings

The archaeological and palaeontological findings were initially subjected to the 3D scanning process (Tables 1 and 2) using a handheld 3D scanner, the Artec EVA (Fig. 10), which utilises structured light technology, which proves to be an appropriate technology for archaeological applications (Papas, Tsongas, Karolidis & Tzetzis, 2021; 2023). This scanner offered a high level of precision, with an accuracy of up to 200 microns (0.2 mm), and a reconstruction rate of 16 frames per second (FPS). Additionally, the EVA 3D scanner has an acquisition speed of 18 million points/s. The key factor for selecting this scanner was its ability to capture the texture of the scanned models. As a result, all the 3D scanned objects retained their original geometric shape as well as their natural colours.

Regarding the selection of artefacts, 33 findings were chosen based on their scientific significance, geometric properties, and physical condition. The museum's digital library encompasses a wide array of palaeontological findings, including bones, teeth, and skulls of various species such as wild goats, hyenas, rhinoceroses and lions. Notably, the 3D scanning process also included a cast of the iconic palaeoanthropological find, the Petralona human skull (the original specimen is curated in the Geology–Palaeontology–Palaeoanthropology Museum, Aristotle University of Thessaloniki).

The 33 findings were further categorised based on their physical condition. Several bones underwent necessary preparation before the 3D scanning process, while others retained the stalagmite covering on their surface (Fig. 11). Some other findings were mounted and glued onto a rigid stand (Fig. 10), making it difficult to scan their bottom surfaces. Despite these challenges, they were selected for the digital library due to their significance.

Figure 10: Palaeontological findings mounded on rigid stands and the ARTEC EVA 3D Scanner.

Table 2: Illustrations of certain 3D-scanned palaeoanthropological and palaeontological findings.

Palaeontological Finding	Human skull	Giant deer antler	Turtle shell	Carnivore femur	Horse skull
3D Scanned Model					
Palaeontological Finding	**Rhinoceros molar**	**Elephant rib**	**Hyena mandible**	**Lion humerus**	**Cave bear skull**
3D Scanned Model					

(a) (b)

Figure 11: 3D-scanned models of palaeontological findings before (a) and after (b) the necessary preparation. Graphical scale: 10 cm.

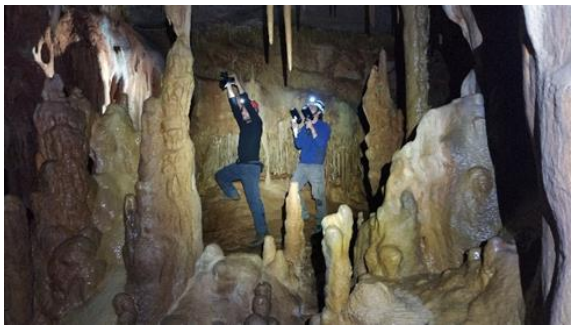
The individual scans and point clouds of each 3D model were analysed using Artec Studio software. Several essential steps, including alignment, trimming, hole filling, and the application of textures, were carried out to finalise the 3D scanned models. These steps are crucial for the processes of 3D scanning and reverse engineering, as highlighted in various research studies (Stergios, Tzimtzimis, Tzetzis, Dodun, & Kyratsis, 2018, Stasinakis et al., 2022). Two distinct resolutions were exported for each digital model. The low-resolution files were used in the Petralona Virtual Museum, while the high-resolution models were imported into the museum's digital library.

(a)

(b)

Figure 12*:* Snapshots from the scanning process using a terrestrial 3D laser scanner with an integrated LED lighting device: a) Trench B; b) North chamber.

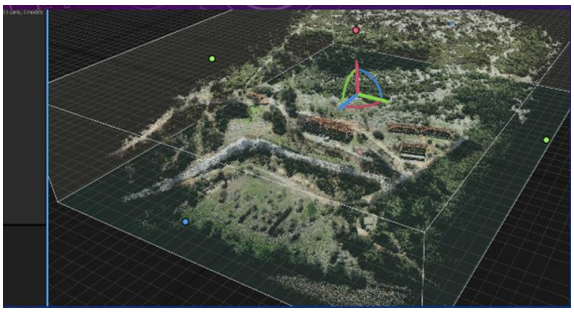
(a)



(b)

Figure 13: Use of studio flash with an operator to quickly change position and bounce flash technique in very narrow parts of the Petralona Cave: a) Capturing photographs using a medium format camera.; b) Applying the bounce flash technique in very narrow parts of the Petralona Cave.

For the 3D digitisation of the Petralona Cave, a terrestrial 3D laser scanner with an integrated LED lighting device (Figure 12) and an unmanned aerial vehicle (UAV) were used in combination with terrestrial photography, to achieve the maximum possible resolution of the photorealistic texture of the produced 3D model (Tokmakidis, Spatalas, Tokmakidis, Tsioukas, 2014). In addition, the processing of all the data was carried out using Reality Capture software, version 1.1.1.15122, using a PPI (pay per image) license which simultaneously resolves the scans and photographs, with the use of photogrammetry (SfM) (Fig. 13). Photographs were taken with the use of a DJI Phantom 4 RTK UAV, with its integrated 20Mpixels camera. To optimise texture quality and enhance the geometry in areas inside the cave where the 3D laser scanner was unable to survey, a very high-resolution medium format camera (Hasselblad X1D II, 50Mpixels) was used for ground shots in combination with artificial strobe lighting (4 studio flashes and 4 portable flashes, all of them remotely synced with the camera).

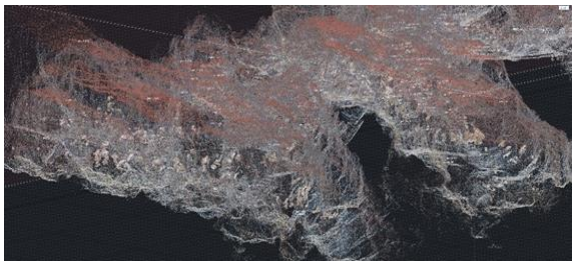


(a)

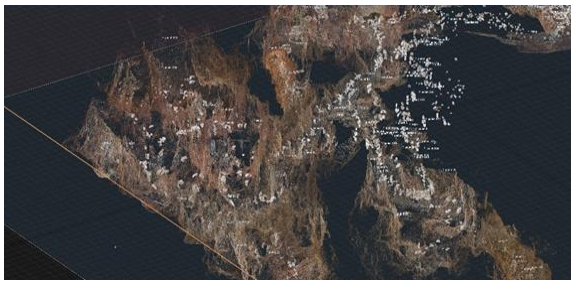
(b)

(c)

Figure 14: Processing of aerial photos: a) Sparse point cloud of the entrance, an intermediate processing step for producing a quick DTM; b) View from 110 m above the ground; and c) 35 m above the ground.



(a)



(b)

Figure 15: Views from the final sparse point cloud of the Petralona Cave interior (combination of laser scanning and photogrammetry using the Reality Capture software): a) before texturing; b) after texturing with the GCPs layer visible.

Two sets of flights were conducted, with the first one at 110 m above ground level, in order to capture quickly a digital terrain model (DTM), to use for flying exactly 35 m above ground level and have homogeneous spatial resolution (Fig. 14).

The point clouds of each position of the scanner and the processed photographic images were processed in Reality Capture Software (PPI licence) and resolved in combination with the measured coordinates of the ground control points (Fig. 15) (Verykokou, Soile, Bourexis, Tokmakidis, Tokmakidis, & Ioannidis, 2021). In this way, the overall 3D model of the cave with a photorealistic texture was produced. This model was cleaned of anomalies in its topology and reduced in resolution using automatic and semi-automatic polygon re-topology techniques in Blender software to an 80-million triangles model. This process was necessary since the original model consists of 1.9 billion triangles with an average edge length of 0.0046 m, and 796 textures of 8192 × 8192 pixels.

Table 1 displays the technical details of the equipment employed in the 3D scanning procedures for both the cave and palaeontological findings, including the 3D scanners, the digital camera, and the UAV apparatus.

3.5. Implementation of the architectural structure

In collaboration with the design team, our objective was to create a virtual online museum that prioritises easy and clear navigation among the diverse types of the provided information, namely videos created by the 3D scanner, manipulable 3D objects, texts, diagrams, photographs and panoramic photographs. To this end, we followed several important guidelines and contemporary best practices for web user interface design. These include implementing a clean and simple information structure, establishing straightforward navigational paths with explicit entry and exit points, providing direct and understandable feedback, ensuring design and

typography consistency, incorporating intuitive interaction schemes, and utilising clear affordances, mappings, and constraints (Lidwell, Holden & Butler, 2003).

In addition, we adopted a flat and minimalistic design approach that leverages open spaces to allow virtual visitors to focus on the crucial information presented on each screen. This design choice eliminates unnecessary visual noise that could hinder user interaction. The design traits contribute to enhancing user engagement with both the Virtual Museum itself, thanks to its overall aesthetic characteristics, and the presented information. The balance achieved between the two aspects helps one complement the other (Hornecker & Stifter, 2006).

The technologies employed for implementing the Virtual Museum include well-known server-side and client-side web scripting languages, such as php and mysql on the server side, and jquery and json on the client side. The end result is a custom web platform that is fast and easy to manage, accompanied by a custom Content Management System (CMS) that facilitates effortless editing and the addition of new content as and when required. Specific plugins such as model-viewer (https://modelviewer.dev/) together with .glb 3D models have been utilised exclusively for the presentation of interactive 3D items, as well as Pannellum (https://pannellum.org/) a lightweight panorama viewer, that was used to allow user interaction with the panoramic images of the cave. Given the widespread use of mobile devices in recent years, the Virtual Museum supports a responsive design that can adapt to various screen sizes and devices without compromising functionality. However, it is worth noting that fully experiencing the provided information may arguably be better suited for larger screens. A set of tools encompassing a range of digital accessibility features for users with disabilities has also been added, enabling as many people as possible to navigate and experience the virtual museum comprehensively (Fig. 16).

4. Discussion

As Anna Bentkowska-Kafel (2016: 2) points out, the "concept of a virtual museum is not new. Historically, its meaning has evolved to encompass new intellectual constructs and cultural phenomena, reflecting changes influenced by technological developments in information communication" (for a review see Schweibenz, 2019). Despite the inherent advantage of a virtual museum, which allows for visits independent of time or location, it should be noted that visiting a virtual museum cannot fully replace the experience of visiting a physical museum. More so, it has been indicated that a virtual museum "leads to an increased awareness of the physical museum and increased attendance" (Latham & Simmons, 2014: 82). Hence, the physical museum and the virtual museum "can ultimately be mutually reinforcing' (Clough, 2013: 34). Accordingly, we chose the Petralona Cave Virtual Museum not to "perform as the digital footprint of the physical museum" (V-MusT, 2021: 39). While it stands as a distinct entity in the digital realm, our approach is one of deliberate complementarity with its physical counterpart located close to the cave. The creation of the Petralona Cave Virtual Museum coincided chronologically with the renovation and re-exhibition of the collections of the Petralona Museum. While maintaining the core informational axes, we have developed a distinct exhibition narrative for each one emphasising their independent but mutually supportive nature. From the outset, we deliberately established an independent visitor experience for the Virtual and physical Petralona Cave museums while also fostering synergies and interactions between them. For instance, the Virtual Museum provides a wealth of information and interactive exhibits that enhance the understanding of the artefacts displayed in the physical museum. Furthermore, the Virtual Museum offers additional content, such as informative videos, in-depth articles, and related bibliography, enriching the visitor's experience and knowledge. It also houses archives that are not available in the physical museum, benefiting the scientific community and the general public. Additionally, the Virtual Museum serves as a promotional tool for the physical museum, attracting a wider audience and generating interest in visiting in person, and vice versa.

Figure 16: To the left side of the figure a set of tools encompassing a range of digital accessibility features for users with disabilities, enabling as many people as possible to navigate.

According to ICOMOS (2008), heritage conservation is by its nature a communicative act. In the cultural heritage site domain, digital technologies have been used since the 1990s. Currently, the digitalisation of heritage has become a cutting-edge practice. “The new technologies introduced are first and foremost communication technologies, enabling dialogue, interaction and power-sharing” (Pruulmann-Vengerfeldt & Runnel, 2014: 15). Digital environments are argued to have been proven powerful tools for democratising and educating as well (Ibañez-Etxeberria, Gómez-Carrasco, Fontal & García-Ceballos, 2020; Pierroux, Bäckström, Brenna, Gowlland & Ween, 2020). The emergence of digital technologies has enabled widespread free and equal access for all members of the public, regardless of their geographical location or economic means (García-Bustos, Rivero, García Bustos, & Mateo-Pellitero, 2022), also allowing experiencing objects or sites that would otherwise be inaccessible to the general public. Admittedly “museums have gained significantly from the giant technological strides associated with the growth of the Internet. Nobody disputes that the widespread dissemination of information and knowledge about museum collections is an added step towards the democratisation of culture” (Avenier, 1999: 31). The lack of physical access during the Coronavirus shutdown, when the only way to maintain contact with museums was through digital means, has demonstrated the value of digital technologies. Digital technology also affects experiential learning since it can be used to construct an effective learning environment which facilitates more immersive participation and deeper engagement with the heritage asset (Enhuber, 2015). In addition, the digital tool has the advantage of increasing opportunities in terms of tourist promotional methods giving the chance to people all over the world to “discover”, stimulate their attention and potentially attract more visitors.

The Petralona Cave Virtual Museum is a pioneering virtual museum in Greece since it is the only one that informs the public about the Palaeolithic period, also attracting niche audiences interested in specialised subjects apart from the Palaeolithic archaeology, such as palaeontology and geology. Through advanced technologies used, it allows for unprecedented levels of interaction and manipulation of the site’s cultural heritage, presenting visitors with new opportunities to engage with the material. For example, the famous Petralona skull, currently housed in the Geology–Palaeontology–Palaeoanthropology Museum at the Aristotle University of Thessaloniki, is typically only accessible to researchers with special permission. However, the Petralona Cave Virtual Museum’s 3D digital model of the human skull allows visitors to observe and examine it in full detail, without restriction. As research in the fields of palaeontology, archaeology, and geology pertaining to the Petralona Cave continues, the Petralona Cave Virtual Museum has been thoughtfully designed to enable regular content review and updates. This approach ensures that the museum remains current and contributes to the sustainable conservation of the site's cultural heritage.

The Petralona Cave Virtual Museum was designed and developed to meet the diverse needs and interests of visitors, including specialists, students, and the general public. Special attention was given to being more inclusive with individuals with disabilities. The user experience was crafted to be enjoyable, intuitive, and highly effective, with a focus on providing visitors with an immersive and engaging experience. Our goal was to exceed expectations by anticipating the needs and desires of visitors before, during, and after their visit, with the aim of not only attracting visitors but also encouraging them to return and recommend the museum to others.

The process of designing and developing the Petralona Cave Virtual Museum involved an analysis of user needs, as well as the establishment of specific requirements that needed to be met. Based on these findings, a range of design options was created, with careful consideration given to those that would provide visitors with maximum choice and flexibility in terms of what they could see and how they could navigate through the museum. Generally, we have chosen to avoid lengthy texts that may potentially discourage digital visitors from engaging with the content. Instead, we have opted for concise and comprehensive texts that effectively convey the essence of the information. It is important to recognise that not all users have the same informational needs. Therefore, the interface should support different levels of user immersion, abstraction, and depth. Gammon (1999, as cited in Hornecker & Stifter, 2006) refers to this characteristic as the "layering of activities". The Petralona Cave Virtual Museum adopted an exploratory approach that enables such layering. This approach aligns with contemporary constructivist practices and allows for the simulation of active and immersive experiences for virtual visitors. While the actual visit to the cave holds its own importance, the utilisation of these practices and diverse virtual tools can significantly enhance the overall user experience, making it both exciting and educational. The incorporation of various presentation methods, including videos, high-quality images, interactive maps, animated content, interactive 3D models, searchable item libraries, and more, empowers users to create a highly personalised navigation plan and ultimately provides a Virtual Museum experience comparable to visiting the physical museum or cultural site.

To ensure that visitors could fully explore and appreciate the significance of the cave, we utilised a variety of user-friendly digital tools, including cutting-edge digitisation techniques that allowed for the creation of highly detailed 3D models of the site. The use of these technologies was a critical factor in providing visitors with a comprehensive and immersive experience, while also ensuring the sustainable conservation of the site for future generations. 3D scanning models of large objects and environments, such as the Petralona Cave, although very complex, are possible as demonstrated in the current work. Surveying and capturing details using conventional techniques would be very challenging. Therefore, a combination of other, more sophisticated techniques was required. To that end, an UAV was utilised in combination with terrestrial photography in order to achieve the maximum possible resolution of the photorealistic texture of the 3D model. Specialised software was used to simultaneously resolve the scans and photographs, with the use of photogrammetry. Photographs were also taken with the use of an aerial camera that was installed in a UAV system to capture the external surroundings. To optimise quality, a second medium format and a camera with a very high resolution were used for ground shots. The wealth of data provided by such techniques allowed for the construction of a 3D representation and photorealistic appearance of the complex Cave’s structure.

5. Conclusions

The Petralona Cave and Museum is a famous archaeological and palaeontological site mainly due to the discovery of the well-preserved fossil human skull in 1960, but also because of rich finds during subsequent excavations. The Petralona Cave Virtual Museum, the design and development of which we presented in this paper, constitutes a pioneering endeavour that is exclusively dedicated to the Palaeolithic period, and consequently, fills a substantial lacuna in public awareness and comprehension of this pivotal epoch in Greece.

Our approach was not to replicate the physical museum located close to the cave but to create an independent and comprehensive experience that is accessible to all visitors, including those who cannot visit the site in person. Consequently, our approach offers an authentic and complete experience, catering to a wide range of audiences and providing an opportunity for people to engage with the content meaningfully.

To achieve this goal, we used integrated storytelling techniques and various presentation methods and crafted a compelling narrative to captivate visitors and encourage them to explore our Virtual Museum further, fostering a lifelong connection with our collection. We employed cutting-edge digital technologies to create an interactive and enjoyable educational experience. Our approach emphasised presenting knowledge-rich and visually compelling information in simple formats to facilitate ease of access.

These state-of-the-art 3D technologies have the potential to revolutionise the way visitors engage with the Petralona Cave and its findings, offering a means of education and entertainment for both the general public and scientists. Our Virtual Museum is expected to enhance the publicity of the Petralona site, contributing to the dissemination of knowledge about this important archaeological site.

The Petralona Virtual Museum liberates the Petralona cave and its findings from their original site, disseminating them "beyond the walls".

As we move forward, our primary focus will be to open our Virtual Museum to the public and conduct validation to evaluate its effectiveness and user satisfaction. This study will provide valuable insights into the functionality and usability of the Virtual Museum, contributing to its refinement and improvement.

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References

Aidonis, A., Achillas, Ch., Tzetzis, D., Athanassiou, A., Karkazi, E., Darlas, A., & Papageorgopoulou, Ch. (2023). Digital 3D facial approximation of the Petralona skull. Methodological issues and applications. *Journal of Archaeological Science: Reports*, 51, 104206. https://doi.org/10.1016/j.jasrep.2023.104206

Avenier, P. (1999). Putting the public first: the French experience. *Museum International,* 51(4), 31–34. https://doi.org/10.1111/1468-0033.00227

Baryshnikov, G. F., & Tsoukala, E. (2010). New analysis of the Pleistocene carnivores from Petralona Cave (Macedonia, Greece) based on the collection of the Thessaloniki Aristotle University. *Geobios,* 43(4), 389–402. https://doi.org/10.1016/j.geobios.2010.01.003

Bentkowska-Kafel, A. (2016). Virtual Museum – The concept and transformation. In J. Pilcher, (Ed.), *Display: consume: respond – digital engagement with art. The 28th Annual Conference of Computers and the History of Art (CHArt)* held on 15 and 16 November 2016 at the Association of Art Historians (Vol. 15, pp. 1–25). London.

Clough, G. W. (2013). *Best of both worlds. Museums, libraries, and archives in a digital age*. Washington D.C.: Smithsonian Press. http://www.si.edu/bestofbothworlds

Crégut-Bonnoure, E., & Tsoukala, E. (2005). The Pleistocene bovids from the Petralona Cave (Macedonia, Greece): new interpretations and biogeographical implications. *Quaternaire, hors-série 2*, 161–178.

Darlas, A. (2014). In search of the identity of Petralona cave and its importance for the Greek and European Prehistory. In E. Stefani, N. Merousis, & A. Dimoula (Eds.), *1912–2012. A century of research in prehistoric Macedonia*. International Conference Proceedings, Archaeological Museum of Thessaloniki 22–24 November, Thessaloniki, Greece (in Greek).

Enhuber, M. (2015). Art, space and technology: how the digitisation and digitalisation of art space affect the consumption of art—a critical approach. *Digital creativity*, 26(2), 121–137.

Fortelius, M., & Poulianos, N. A. (1979). *Dicerorhinus* cf. *hemitoechus* (Mammalia, Perissodactyla) from the Middle Pleistocene cave at Petralona – Chalkidiki – N. Greece. *Άνθρωπος, 6*, 15–43.

García-Bustos, M., Rivero, O., García Bustos, P., & Mateo-Pellitero, A. M. (2022). From the cave to the virtual museum: accessibility and democratisation of Franco-Cantabrian Palaeolithic art. *Virtual Archaeology Review*, 14(28), 54–64. https://doi.org/10.4995/var.2023.17684

Harvati, K. (2009). Petralona: Link between Africa and Europe? *Hesperia Supplements,* 43, 31–47.

Harvati, K., Panagopoulou, E., & Runnels, C. (2009). The paleoanthropology of Greece. *Evolutionary Anthropology,* 18(4): 131–143. https://doi.org/10.1002/evan.20219

Harvati, K. (2022). The hominin fossil record from Greece. In E. Vlachos (Ed.), *Fossil Vertebrates of Greece, vol. 1: Basal Vertebrates, Amphibians, Reptiles, Afrotherians, Glires, and Primates* (pp. 669-688). Cham: Springer.

Hornecker, E. & Stifter, M. (2006). Learning from Interactive Museum Installations About Interaction Design for Public Settings. In J. Kjeldskov & J. Paay (Eds.), *Proceedings of the 18th Australia conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments (OZCHI 2006)*, (pp. 135-142), Association for Computing Machinery, New York, United States. https://doi.org/10.1145/1228175.1228201

Ibañez-Etxeberria, A, Gómez-Carrasco, C. J., Fontal, O. & García-Ceballos, S. (2020). Virtual environments and augmented reality applied to heritage education. An evaluative study. *Applied Sciences,* 10(7), 2352. https://doi.org/10.3390/app10072352

ICOMOS 16th General Assembly (2008). *Interpretation and presentation of cultural Heritage Sites*. Québec.

Kanellis, A., & Marinos, G. (1969). Die Höhle von Petralona. *Actes du IVe Congrès International de Spéléologie* (Ljubljana 1965), 4–5, 355–362.

Koufos, G. D., & Tsoukala, E. (2007). Petralona Cave. Thessaloniki: Aristotle University of Thessaloniki.

Kretzoi, M. (1977). The fauna of small vertebrates of the Middle Pleistocene at Petralona. *Ἄνθρωπος,* 4, 131–143.

Kretzoi, M., & Poulianos, N. A (1981). Remarks on the Middle and Lower Pleistocene vertebrate fauna in the Petralona Cave. *Ἄνθρωπος,* 8, 57–72.

Kurtén, B. (1983). Faunal sequence in Petralona Cave. *Ἄνθρωπος,* 10, 53–59.

Kurtén, B., & Poulianos, A. N. (1977). New stratigraphic and faunal material from Petralona Cave, with special reference to the Carnivora. *Ἄνθρωπος,* 4, 47–130.

Kurtén, B., & Poulianos, A. N. (1981). Fossil Carnivora of Petralona Cave: status of 1980. *Ἄνθρωπος,* 8, 9–56.

Latham, K. F., & Simmons, J. E. (2014). *Foundations of museum studies. Evolving systems of knowledge*. Libraries Unlimited, Santa Barbara, CA.

Lidwell, W., Holden, K., & Butler, J. (2003). *Universal Principles of Design*. Rockport Publishers, Massachusetts, US.

Papas, N., Tsongas, K., Karolidis, D., & Tzetzis, D. (2021). A Comparison of Laser and Structured Light Scanning Technologies for Archaeological Applications. *International Journal of Modern Manufacturing Technologies*, 13(3), 111-116. https://doi.org/10.54684/ijmmt.2021.13.3.111

Papas, N., Tsongas, K., Karolidis, D., & Tzetzis, D. (2023). The Integration of 3D Technologies and Finite Element Analysis (FEA) for the Restoration of an Ancient Terra Sigillata Plate. *Digital Applications in Archaeology and Cultural Heritage*, 28, e00260. https://doi.org/10.1016/j.daach.2023.e00260

Pierroux, P., Bäckström, M., Brenna, B., Gowlland, G., & Ween, G. (2020). Museums as sites of participatory democracy and design. In P. Hetland, P. Pierroux, & L. Esborg (Eds.), *A history of participation in museums and archives. Traversing citizen science and citizen humanities* (pp. 27–45). London: Routledge.

Pruulmann-Vengerfeldt, P., & Runnel, P. (2014). The challenge of democratising the museum. In P. Pruulmann-Vengerfeldt, & P. Runnel (Eds.), *Democratising the museum: Reflections on participatory technologies* (pp. 9–16). Frankfurt: PL Academic Research.

Rabeder, G., & Tsoukala, E. (1990). Morphodynamic analysis of some cave-bear teeth from Petralona Cave (Chalkidiki, North-Greece). *Beiträge zur Paläontologie von Österreich, 16*, 103–109.

Schweibenz, W. (2019). The virtual museum: an overview of its origins, concepts, and terminology. *The Museum Review,* 4(1), 1–29.

Sickenberg, O. (1964), Die Säugetierfauna der Höhle Petralona bei Thessaloniki (vorläufige Mitteilung). *Geological and Geophysical Research,* 9(1), 1–16.

Sickenberg, O. (1971). Revision der Wirbeltierfauna der Höhle Petralona (Griech. Mazedonien). *Annales Géologiques des Pays Helléniques,* 23, 230–264.

Stasinakis, A., Chatzilari, E., Nikolopoulos, S., Kompatsiaris, I., Karolidis, D., Touloumtzidou, A., Papas,N., & Tzetzis, D. (2022). A Hybrid 3D Object Auto-Completion Approach with Self-Supervised Data Augmentation for Fragments of Archaeological Objects. *Journal of Cultural Heritage*, 56, 138-148. https://doi.org/10.1016/j.culher.2022.06.011

Stergios, F., Tzimtzimis, E., Tzetzis, D., Dodun, O., & Kyratsis P. (2018). 3D Laser Scanning and Digital Restoration of an archaeological find. *MATEC Web of Conferences*, 178, 03013. https://doi.org/10.1051/matecconf/201817803013

Stringer, C. B. (1974). A multivariate study of the Petralona skull. *Journal of Human Evolution,* 3, 397–404.

Stringer, C. B. (1980). Phylogenetic position of the Petralona cranium. *Ἄνθρωπος,* 7, 81–95.

Stringer, C. B., Howell, F. C., & Melentis, J. K. (1979). The significance of the fossil hominid skull from Petralona, Greece. *Journal of Archaeological Science*, 6(3), 235–253.

Stylianidis, E., Georgopoulos, A., & Remondino, F. (2016). Basics of image-based modelling techniques in Cultural Heritage 3D recording. In: E. Stylianidis, & F. Remondino (Eds.), *3D Recording, Documentation and Management of Cultural Heritage*, (pp. 253-304). Dunbeath: Whittles Publishing.

Tokmakidis, P., Spatalas, S., Tokmakidis, K., & Tsioukas, V. (2014). *Laser scanning in the service of the visually impaired*. GEOMAPPLICA Conference, 8-11 September, Skiathos island, Greece.

Tsoukala, E. (1989). *Contribution to the study of the Pleistocene fauna of large mammals (Carnivora, Perissodactyla, Artiodactyla) from Petralona Cave, Chalkidiki (N. Greece)*. PhD thesis, Aristotle University of Thessaloniki. *Scientific Annals, Faculty of Physics and Mathematics, University of Thessaloniki,* 1(8), 1–360 (in Greek).

Tsoukala, E., & Guérin, C. (2016). The Rhinocerotidae and Suidae of the Middle Pleistocene from Petralona Cave (Macedonia, Greece). *Acta Zoologica Bulgarica,* 68(2), 243–264.

Verykokou, S., Soile, S., Bourexis, F., Tokmakidis, P., Tokmakidis, K., & Ioannidis, C. (2021). A Comparative analysis of different software packages for 3D Modelling of complex geometries. In: M. Ioannides, E. Fink, L. Cantoni, & E. Champion, (Eds.), *Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection*. EuroMed 2020. Lecture Notes in Computer Science, vol 12642. Springer, Cham. https://doi.org/10.1007/978-3-030-73043-7_19

V-MusT (2021). What is a Virtual Museum? Virtual Museum Transnational Network Virtual Museums. Retrieved May 12, 2023, from http://www.v-must.net/virtual-museums/what-virtual-museum