PATRIMONIO CULTURAL:
Ética, capacidades y sostenibilidad

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(Coords.)

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Enhancing Cost-effective Cultural Heritage recording and Dissemination: The evolving Challenges of 3D Computer Graphics

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Since 1998, he has been working at the Archaeological Unit of the University of Minho, involved in projects focused on multimedia methods, 3D computer graphics, and visualization in Archaeology.

Currently, he is an integrated researcher at the Lab2PT of the University of Minho. His research interests encompass digital surveying of archaeological data, virtual representation and reconstruction of archaeological sites, and data visualization.

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Resumen

El estudio del Patrimonio implica diversas metodologías de registro, análisis, investigación y difusión de bienes culturales. Las aplicaciones informáticas han sido fundamentales desde finales de los años 50 en Europa y principios de los 60 en Norteamérica, demostrando la utilidad de la informática en las ciencias sociales y las humanidades.

Los avances en infografía y modelización 3D han permitido crear valiosas representaciones tridimensionales del patrimonio cultural, lo que ha facilitado la investigación científica, la difusión de resultados y la sensibilización del público. El tratamiento informático de datos ha afectado notablemente a campos como las bases de datos, los SIG, la visualización y la inteligencia artificial. Hoy en día, las aplicaciones informáticas siguen siendo cruciales para la investigación del patrimonio y la difusión de sus bienes.

Áreas emergentes como las redes neuronales artificiales, la visión por ordenador, la realidad virtual y aumentada, la adquisición 3D y la interacción están ganando importancia. Es vital seguir estrategias y principios bien definidos para conservar y preservar los bienes culturales para las generaciones futuras.

Palabras clave

Patrimonio cultural; Fotogrametría; SIG; Arqueología; Arte rupestre.

Abstract

The study of Heritage involves diverse methodologies for recording, analysing, researching, and disseminating cultural assets. Computer applications have been pivotal since the late 1950s in Europe and early 1960s in North America, demonstrating computing's utility in social sciences and humanities.

Advancements in computer graphics and 3D modelling have led to the creation of valuable 3D representations of cultural heritage, aiding scientific research, sharing results, and raising public awareness. Computer data processing has notably affected fields like databases, GIS, visualization, and artificial intelligence. Today, computational applications remain crucial for heritage research and asset dissemination.

Emerging areas like artificial neural networks, computer vision, virtual and augmented reality, 3D acquisition, and interaction are gaining importance. It is vital to follow well-defined strategies and principles to conserve and preserve cultural assets for future generations.

Keywords

Cultural Heritage; Photogrammetry; GIS; Archaeology; Rock art.

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1. Introduction

In an era where cultural heritage preservation endeavours strive to align with prevailing technologies, the processes of recording and disseminating heritage have undergone a profound transformation. Since the advent of computer applications in the late 1950s and early 1960s, their integration within the social sciences and humanities has boosted innovative approaches to heritage studies. This journey, initiated by elementary digital tools, has reached its peak in sophisticated methodologies grounded in computer graphics and three-dimensional (3D) modelling, fundamentally reshaping the paradigms of digital heritage preservation. Today, these advancements not only serve as the foundation for scientific research but also assume a pivotal role in disseminating research and fostering public engagement.

This work aims to provide a concise examination of the utilization of emerging technologies in the field of heritage study and preservation, with a particular emphasis on digital recording and three-dimensional representation. Additionally, it briefly explores optimal visualization strategies. Drawing from the experience of the Archaeology Unit at the University of Minho, this work presents two recent cases that exemplify the benefits of three-dimensional recording and subsequent application of computer graphics methodologies in both study and dissemination.

The last section presents some conclusions based on accumulated experience that clearly show the advantages of integrating different modern technologies, particularly photogrammetry, geographic information systems and computer graphics. A clear advantage is recognised precisely in the development of augmented reality applications. In terms of future directions, the advantages of artificial intelligence techniques are recognised for further enriching digital heritage preservation and interpretation, ultimately fostering a deeper appreciation and understanding of our shared cultural heritage.

2. Heritage going digital: a retrospective

In the realm of cultural heritage, methodologies employed across various phases —record, analysis, research, and dissemination— strive to integrate diverse knowledge domains while staying abreast of technological advance-

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ments. The incorporation of computer applications, introduced in the late 1950s (Europe) and early 1960s (North America), has played a pivotal role (Cowgill 1967). These applications, initially aimed at analysing and classifying data sought to establish the computer as a valuable tool in cultural heritage research (Chenhall 1968).

Over a short span, the number of computer applications in cultural heritage experienced exponential growth. By the early 1970s, computers became central tools for research, focusing on areas such as descriptive statistics, data organization, seriation, classification, multidimensional scaling, and databases (Whallon 1972). Subsequent advances in computer graphics and 3D modelling aimed to create detailed 3D representations of cultural heritage elements, including artefacts, sites, and landscapes. These 3D representations served not only research objectives but also became crucial for disseminating results (Addison 2000).

By the end of the last century, the influence of computer-based data processing in cultural heritage matters became highly noticeable. This impact extended to areas such as databases, geographic information systems (GIS), visualization, and even artificial intelligence (Richards 1998). The rise of international conferences and journals dedicated to computer-assisted cultural heritage confirmed this growing influence.

Presently, there is a significant intensification of computer application projects in cultural heritage, coupled with a remarkable expansion of application areas. While the initial areas remain crucial, emerging fields such as artificial neural networks, computer vision, virtual and augmented reality, serious gaming, 3D acquisition, and interaction are gaining prominence. This trend is evident in research published in respected journals like the Journal on Computing and Cultural Heritage, the Journal of Cultural Heritage, the Journal of Archaeological Method and Theory, the Multimedia Tools and Applications Journal, and the Virtual Archaeology Review. Conferences such as the Computer Applications and Quantitative Methods in Archaeology (CAA), the International Meeting on Archaeology and Graphic Informatics, Cultural Heritage and Innovation, and the EUROGRAPHICS Workshop on Graphics and Cultural Heritage (EG-GCH) also contribute to this growth.

The recognition of the potential of computer applications and technology in heritage, particularly in archaeology, has led to diverse expressions

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worldwide. Common terms include Virtual Archaeology, Digital Archaeology, and Cyber-Archaeology.

Virtual Archaeology (Reilly 1991), first coined by Paul Reilly, aims to create surrogate representations of original archaeological elements. Initially focused on visualization using technologies like hypertext, multimedia, and 3D solid modelling, the concept expanded to include the application of visualization and presentation methods to represent past environments, including buildings, landscapes, and artefacts (Ryan 2001).

Digital Archaeology seeks to understand the strengths and weaknesses of computers and information technology for the benefit of archaeology. It explores the potential of information and communication technology to expand the limits of archaeological theory and practice, enhancing the recovery, understanding, and presentation of the past (Zubrow 2006).

Cyber-archaeology is less concerned with reconstructing the past and more focused on simulating it. As a result, it is not necessarily visual or oriented towards photorealism but is entirely 3D, dynamic, interactive, and complex. Cyber-archaeology places significant emphasis on collaborative environments, research, and virtual models to recreate a potential past (Forte 2010).

Although the expressions differ, the aims and activities of these approaches are highly comparable (Grosman 2016). After the 3D acquisition of archaeological data, implementing a visual 3D representation of these elements becomes essential. Archaeologists use these representations for both research and dissemination purposes, occasionally improving them during the research and interpretation phase.

2.1. Principles of Computer-based Applications in Heritage

The recognition of Heritage's significance stands as a core value, consistently aimed at imparting its importance to succeeding generations. The specific awareness that archaeological excavation entails inherent destruction, as highlighted by Baker (1977), justifies the persistent concern within the archaeological community to carefully regulate interventions at excavation sites. From the early 20th century onward, various documents have been formulated, articulating crucial guiding principles about the conservation and preservation of heritage.

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Post the mid-20th century, these principles have evolved to address the integration of computer-based applications within the realms of heritage and archaeology. Specifically, these principles delineate the circumstances under which computer-based applications should be employed, as well as the extent to which these technologies and methods are deemed appropriate. The most widely accepted guidelines are consolidated within four distinct documents:

- Principles for the Conservation and Restoration of Built Heritage:
  - Encompassed within The Charter of Krakow 2000 (De Naeyer, Arroyo y Blanco JR 2000), this document emerged from the International Conference on Conservation "Krakow 2000" and serves as a guiding framework for cultural heritage safeguarding. It aligns with the spirit of the Charter of Venice (1964) but is adapted to the realities of the turn of the century. In this sense, the authors advocate for the utilization of contemporary technologies, databases, information systems, and virtual environments to safeguard and publicly showcase archaeological sites. This implies the endorsement of computer-based applications as a viable alternative for accessing physically restricted sites and disseminating archaeological information to a broader audience. Notably, this charter marks the inaugural acknowledgement of the application of computer-based tools in the realm of heritage.
- ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites:
  - Defined in 2008 as the Ename Charter by the International Council on Monuments and Sites (ICOMOS), this charter outlines fundamental principles for interpreting and presenting heritage sites. The Ename Charter suggests that constructing virtual reconstructions should rely on evidence derived from archaeological, architectural, and historical data. Additionally, it emphasizes the significance of incorporating written, oral, and iconographic sources, along with photography. The charter underscores the importance of generating alternative reconstructions from these identical information sources for comparison (ICOMOS 2008).
- International Charter for the Computer-based Visualization of Cultural Heritage:

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  - Known as the London Charter (2009), this pioneering document is dedicated to defining guidelines for computer-based visualization in cultural heritage, emphasizing research and dissemination. The London Charter encompasses six principles designed to affirm the reliability of digital visualization methods in heritage, ensuring the meticulousness of the knowledge status represented by these digital visualizations and delineating a clear distinction between evidence and hypothesis. The London Charter outlines six key principles ensuring the reliability of digital heritage visualization. These principles cover implementation guidelines, selective use of computer-based methods, and meticulous evaluation of research sources, comprehensive documentation strategies, sustainable archiving practices, and strategic planning for diverse access levels (EPOCH 2009).
- International Principles of Virtual Archaeology (Sevilla Charter):
  - Established in 2011 by the International Forum of Virtual Archaeology, this charter aims to implement the London Charter principles in archaeology (Lopez-Menchero y Grande 2011). It underscores interdisciplinary collaboration, defines project goals, advocates complementarity with traditional methods, and emphasizes authenticity, historical rigour, efficiency, and scientific transparency. The Sevilla Charter insists on the necessity of team diversity, clearly defined project goals, collaboration with traditional methods, transparency, and distinct levels of authenticity in virtual representations. Furthermore, it stresses the importance of historical accuracy, economic feasibility, and scientific rigour. This charter, along with its evaluation methods for both expert and public communities, emphasizes the quality of projects based on rigour rather than spectacle.

2.2. Digital data acquisition techniques

The scientific community primarily focuses on 3D digitizing techniques in cultural heritage for conservation and record purposes. Additionally, potential applications include (Pieraccini, Guidi y Atzeni 2001):

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1. Digital archives of 3D models: Offering a significant improvement over traditional archiving methods, high-quality 3D models serve as references for degradation monitoring and artefact restoration.
2. High-fidelity physical replica of artworks: 3D models facilitate more accurate and cost-effective replication of artworks for archiving and merchandising purposes.
3. Remote access to cultural heritage: Digital 3D models provide valuable teaching and research resources, eliminating the need for extensive travel to access artworks and enabling exploration of otherwise unreachable sites.
4. Digital restoration: Computer graphics tools allow virtual restoration of damaged artworks, creating 3D models that capture the original appearance.
5. Monitoring of cultural heritage: Regular digital acquisitions enable the early detection of small deformations in open-air monuments, facilitating timely interventions.

In the past, recording relied on manual tools such as paper, pencil, and measuring instruments. The advent of digital recording techniques has significantly improved this landscape, offering undeniable benefits for digitizing cultural heritage, especially archaeological items.

Ensuring accuracy in cultural heritage records is crucial. Teams must use devices that inspire confidence and precision, considering the three-dimensional nature of heritage elements. Various 3D acquisition options, each with distinct recording accuracy levels, are available. These options depend on the scale of heritage elements and employ different technologies:

1. Laser triangulation: Involves a laser source and optical detector to create a detailed and highly accurate point cloud by estimating height through reflected light angles.
2. Time-of-flight Laser: Determines surface distance by measuring the round-trip time of a light pulse, offering moderate accuracy suitable for swiftly capturing 3D information in large scenes.
3. Structured light: Projects a predefined light pattern onto objects, captured by a digital image detector. Portable and user-friendly, it delivers impressive accuracy and productivity by calculating geometry from pattern deformations.

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4. Stereo-photogrammetry: Utilizes the same principle as the human vision system, acquiring 3D models through 2D images from different angles. While a simple and cost-effective technique, its accuracy is relatively lower.

According to Pavlidis et al. (2007), the comprehensive digital recording of heritage encompasses a multidimensional process that not only addresses the 3D digitization of objects and monuments but also delves into digital content management, representation, and reproduction. The primary parameters for analysis are related to the object itself, focusing on its material and size.

Furthermore, key considerations include the hardware and software features of the 3D acquisition system, encompassing accuracy, equipment portability, compliance with standards, productivity of the technique, and texture acquisition capability. Additional parameters, unrelated to the object or acquisition system, include the operator's skill and the equipment cost.

The research teams often opt for laser equipment when budget permits, utilizing Airborne Laser Scanning (ALS) for territorial scale reconnaissance and Terrestrial Laser Scanning (TLS) for sites. Both platforms generally employ Light Detection and Ranging (LiDAR) sensors. At the object scale, Handheld Laser Scanners provide highly accurate results.

Cost-effective approaches ensuring the necessary accuracy for archaeological projects include the successful use of 3D digitizing techniques based on digital images, as demonstrated by Hermon et al. (2012) and De Reu et al. (2013). They highlight the advantages of employing *Structure from Motion* (SfM) methods, akin to stereo-photogrammetry. The benefits include time efficiency, high accuracy, and increased scientific value. SfM data can be combined with satellite sensor data to assess threats to heritage sites (Hesse 2015).

Structured light equipment, such as the Microsoft Kinect camera, presents a low-cost alternative for sites or objects. The Kinect captures a real-time RGB-D stream, creating a satisfactory record for archaeological purposes. However, its suitability is influenced by lighting conditions and is more suitable for indoor use (Zollhöfer et al. 2015).

Combining various 3D acquisition methods, along with GPS systems and total stations for precise georeferencing, enhances the accuracy of the

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record. Aerial 3D acquisition using unmanned aerial vehicles (UAV) is increasingly employed for more complex sites (Davis et al. 2017).

The mentioned 3D acquisition techniques produce a point cloud that requires post-processing to generate a mesh. The density and accuracy of the point cloud depend on the acquisition device, with laser-based equipment typically providing higher quality. The point cloud is typically stored in 3D model file formats such as PLY (Polygon File Format) or OBJ (Object File).

Digital data acquisition techniques play a crucial role not only in documenting visible heritage data but also in revealing hidden realities. Particularly in Archaeology, geophysical techniques are frequently employed in archaeological projects to non-intrusively assess non-visible realities, such as the subsoil or the interiors of architectural structures.

The primary goal of these techniques is to create a representation of the subsoil through non-destructive methods, constituting Archaeological Geophysics. This non-invasive approach involves analysing and interpreting variations in geophysical properties within the archaeological space of interest.

Archaeological geophysics finds diverse applications, including its combination with aerial imagery for landscape archaeology across large territories. On a smaller scale, these methods assist in exploring archaeological sites, aiding in the decision-making process for excavation locations. Additionally, geophysical methods can be employed to analyse archaeological objects and structures within heritage buildings.

Various survey techniques are utilized for different applications, with the most common in archaeology being:

1. Magnetometry: This technique uses sensors to record local variations in the magnetic field of Earth's geological materials, describing the subsoil. It is effective in detecting magnetic anomalies caused by the alteration of sedimentary structures. However, its suitability depends on the contrast between the magnetic properties of archaeological elements and the environment. Two types of magnetometers are generally used for wide areas or specific archaeological sites.
2. Resistivity: This method measures the electrical properties of soil by injecting a current and assessing its alteration. Earth resistivity

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tomography (ERT) is common in archaeology, producing 3D models of earth resistivity. Soil humidity and mineral composition influence results by affecting electrical conductivity stability.

3. Ground Penetrating Radar (GPR): Based on electromagnetic pulses transmitted into the ground, GPR records reflections generated by changes in the propagation media. By analysing arrival times, the depth of objects generating reflections can be determined. GPR antennae frequencies range from 100MHz to 900MHz, with higher frequencies suitable for small objects and lower frequencies for greater depths.

Preserving cultural heritage demands meticulous adherence to 3D acquisition protocols, irrespective of the employed technology. The suitability of visible data acquisition methods varies across different scales. The ALS system is exclusively employed on a territorial scale, whereas the SfM methodology, coupled with a UAV, offers versatility across all scales. Various methods can be employed for recording archaeological sites, excluding ALS. At the object level, UAV usage is less common but contingent upon factors such as the object's size, team expertise, site conditions, required level of detail, and budget constraints. Concerning non-visible 3D data acquisition through geophysical methods, all mentioned approaches are appropriate for the territorial scale. However, at the object scale, the GPR methodology takes precedence, particularly for sizable stone objects.

2.3. 3D Representation

The inception of 3D representations for sites and objects can be traced back to the late eighties and early nineties. While initially embraced for dissemination purposes, its significance in research was not immediately acknowledged. Presently, embarking on a cultural heritage project without allocating resources for 3D representation is nearly inconceivable.

Various techniques exist for the 3D representation of cultural elements. A notably valuable modelling technique is *Constructive Solid Geometry* (CSG), as it adeptly constructs intricate shapes from simpler primitives like cylinders, spheres, cubes, cones, tori, closed spline surfaces, or swept solids. These primitives are skilfully manipulated through *boolean* operations such

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as *union*, *intersection*, and *subtraction*. This modelling approach is supported by software systems like *Blender*, *Maya*, *AutoCAD*, or *3DStudio*, as well as modelling languages like the *Virtual Reality Markup Language* (VRML) or *X3D* (the *XML* syntax-based successor to VRML). These modelling software systems also facilitate other techniques, such as *Non-Uniform Rational B-Splines* (NURBS), which prove invaluable for cultural heritage modelling. NURBS modelling, rooted in splines, allows for the lifelike creation of organic forms and curved surfaces — features frequently encountered in heritage contexts. It boasts even greater intuitiveness than CSG, albeit with a somewhat less rigid structure. At each stage of the traditional modelling workflow, the digital model must go through scholarly validation to ensure the precision of the final 3D representation.

Another significant modelling technique, especially prevalent in archaeological applications, is *procedural modelling*. Procedural modelling is a robust methodology that leverages programming languages to efficiently articulate a semantic description of a structure, generating a 3D polygonal model. The approach finds widespread acceptance in depicting Greco-Roman buildings and urban environments, given the systematic regularity inherent in classical architecture, governed by well-established principles set forth by *Vitruvius* (Saldaña 2015). Tools such as *Blender*, *3DS Max*, or *CityEngine* can be considered for implementing procedural modelling.

Historic Building Information Modelling (HBIM) offers an alternative approach that utilizes attributes and parameters to generate a 3D representation of archaeological data, specifically focusing on architectural elements. HBIM involves constructing a parametric library based on documented architectural principles spanning from the Roman epoch to the modern age. Leveraging historical data adds significant value, ensuring meticulous detail in the 3D objects, including information about the construction materials and methods employed. To enhance the realism of the 3D objects, the final step involves mapping the parametric objects onto the point cloud. Similar to procedural modelling, this 3D representation methodology is particularly well suited for architectural objects (Logothetis, Delinasiou y Stylianidis 2015).

The growing adoption of 3D acquisition techniques in archaeological records is transforming the methodologies and procedures employed in representing archaeological elements (Sulaiman et al. 2013). A notable shift

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in the workflow of this representation process is the reduced influence of archaeological interpretation during the modelling phase, as it heavily relies on the acquired point cloud. Consequently, the modelling process is less dependent on traditional 3D modelling software and more on 3D meshing algorithms like the *Poisson Surface Reconstruction* methodology or the *Delaunay Triangulation* algorithm. The subsequent step involves the texturing procedure, utilizing image information of the object of interest. This 3D representation process is concluded with the segmentation of the mesh into distinct clusters of significance. This segmentation is guided by research and continually validated by experts. The entire procedure can be executed using either commercial or free software systems such as *CloudCompare* or *MeshLab*. Most 3D acquisition devices come equipped with their own GPS systems, allowing for immediate and accurate positioning of the 3D representation. Even in the absence of a built-in GPS, correct georeferencing of ground control points surrounding the element of interest enables nearly instantaneous georeferencing.

Given the ease with which heritage data can be acquired through *Structure-from-Motion* (SfM) methods and the reliability of these data, there is now a substantial volume of 3D representations for various typologies of heritage structures based on this methodology. These models are further processed using *Building Information Modelling* (BIM) to extract valuable information such as plans, sections, and orthophotographs, serving research and publication purposes.

The 3D representation techniques of heritage objects are crucial for creating tangible reproductions. Historically, the cost of digital fabrication techniques was prohibitively high. However, in contemporary times, the value of 3D printing devices has significantly decreased, thanks to the adoption of cost-effective techniques like *fused deposition modelling* (FDM), which still ensures high precision in the produced objects (Balletti, Ballarin y Guerra 2017). Reproducing artefacts through this method finds applications in various domains, including education in museums, providing support for visually impaired individuals, and even producing customized packaging for the safe transportation of cultural objects (Scopigno et al. 2017).

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3. Visualization Strategies

Several definitions of visualization have emerged and evolved over the years, forming a complementary approach. Visualization primarily involves the computer-assisted transformation of data or information into a visual representation that can be interactively explored to gain understanding and insight. For successful visualization, the obtained knowledge should be used to increase the understanding of a subject, facilitating the analysis and dissemination of the data.

Elaborating a comprehensive list of all the techniques and technologies (both 2D and 3D) used in recent years would be an extremely time-consuming task, proving impractical due to the vast array of combinations and diversity in approaches employed. To overcome these limitations, Foni, Papagiannakis y Magnenat-Thalmann (2010) conducted an exhaustive research study on visualization strategies for Cultural Heritage items, while Llobera (2011) performed an exceptional review and evaluation of the advantages of modern visualization techniques in Archaeology, particularly in archaeological discovery and discourse. These research studies reveal several visualization strategies for Heritage items:

- Restitution drawings: A standard procedure and essential step for an excavation team, crucial for student understanding.
- Augmented Pictures: Visual integration and direct comparison of selected restitution hypotheses with present reality.
- Scale models: Physical reproduction typically exhibits mild visual consistency and precision, with detail increasing as the scale approaches 1:1.
- Physical reconstructions: On-site physical reconstitutions offer visitors the chance to visually experience the past, although historical accuracy and precision can be questionable.
- Interactive scale models: Comparable to static scale models but with moving parts illustrating their role, purpose, or construction method.
- Live experiments: Interactive scale models used in Experimental Archaeology, with replicas made at a 1:1 scale.
- Computer Graphics rendering: A visually consistent and historically precise virtual 3D reconstruction.

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- Digital catalogues: Used for dissemination purposes in museums, typically published in electronic formats.
- Digital Panoramas: Comparable to digital catalogues but with increased interactivity.
- Real-time virtual reality simulations: While based on the assumptions of computer-generated renderings, these simulations offer a high level of interactivity.
- Stereoscopic visualizations: Stimulates the viewer's perception of depth with a slightly superior level of virtuality and perceived visual consistency compared to plain real-time simulations.
- Real-time Augmented Reality simulations: Exhibits simplified geometrical models for real-time capabilities, offering interesting possibilities and interactivity.
- Digitally augmented movies: Requires significant time and effort, generally lacking scientific accuracy.
- Semantically supplemented 2D and 3D representations: Enhances visual representation by adding graphical data, such as 2D photographic images or 3D virtual models.

These strategies are categorised by four main classification hubs:

1. The amount of virtuality.
2. The degree of interactivity.
3. Visual consistency and precision.
4. The degree of automatism.

It is crucial to note that data acquisition techniques used during the recording process of a cultural item influence visualization strategies. These strategies aim to enhance automatism, improve precision and visual consistency, and increase interactivity.

4. Using photogrammetry in two distinct studies

The application of modern photogrammetry techniques brings forth numerous advantages to the field of archaeology. These techniques make use of affordable tools like traditional cameras or mobile devices to yield hi-

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Figure 1. Location of the two case studies: *Terras de Bouro and Vila Nova de Foz Côa.*

gh-quality outcomes, often uncovering intricate details that may escape the naked eye (Moro y Pavón 2022). Photogrammetry enables the creation of precise 3D models with remarkable accuracy, facilitating remote analysis of various objects and landscapes.

Moreover, these models serve as meticulous and non-intrusive records, preserving the integrity of archaeological sites (Morgan y Wright 2018). Integrating photogrammetry with other digital tools such as GIS and data analysis algorithms enriches the interpretation and comprehension of archaeological findings (Psarros, Stamatopoulos y Anagnostopoulos 2022). This fusion provides invaluable insights into the material culture of ancient civilizations, allowing researchers to delve deeper into our shared history.

In this section, we will present two distinct studies: the conservation and enhancement of the Roman road *Jeira* in Terras de Bouro, Portugal, and the documentation of rock art in the Côa Valley, Portugal (see Figure 1). Through these case studies, we aim to illustrate how photogrammetry enhances our understanding of ancient landscapes, artefacts, and cultural heritage, shedding new light on the complexities of human history.

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4.1. Archaeological Elements in Mountain Landscapes: Terras de Bouro (Portugal)

Since 2018, studies of the Roman road *Jeira*, also known as *Via Nova* or *Via XVIII*, have been started again in the territory of Terras de Bouro. The main objective of these studies is to update existing knowledge and to diagnose and support the development of future actions.

The focus of these actions is on the conservation and enhancement of the Roman road, as well as on promoting responsible engagement not only from local communities but also from the thousands of visitors who annually traverse this cultural itinerary.

With a particularly significant impact in the Northwest of the Iberian Peninsula, the road network played a crucial role in pacifying and stabilizing Roman influence. It contributed substantially to the success of unprecedented administrative reforms in this region. Simultaneously, it played a fundamental role in shaping consistent and standardized landscapes along the roads. In many cases, these landscapes remained prominent in the historical narrative of these regions for centuries to come (Fontes, Alves y Bernardes 2021).

The acquisition of new data on the current state of the road has been a priority in the conducted work. The path of *Jeira* has been meticulously analysed through on-site inspections and photogrammetric restitutions of the route, established with analysis corridors at defined intervals between 50*m* and 100*m*.

The data survey strategy relied on the use of UAVs to record the road's path at two distinct altitudes. The first was conducted at an average altitude of over 50*m* from the ground and aimed to capture the road's path and its surrounding area. The second survey focused exclusively on capturing the road's trajectory at an average altitude of 2*m* above the ground, thereby offering enhanced detail regarding the path. Each survey was conducted using distinct equipment, namely the *DJI Mavic Pro* and *DJI Phantom 3 Pro*. The equipment with a shorter focal distance, *the DJI Phantom 3 Pro*, was employed for the low-altitude survey to reduce the quantity of captured photographs.

Before the survey, a meticulous on-site analysis of the road's layout was completed to evaluate terrain challenges and determine optimal points for high-altitude flights. Subsequently, this analysis extended to the

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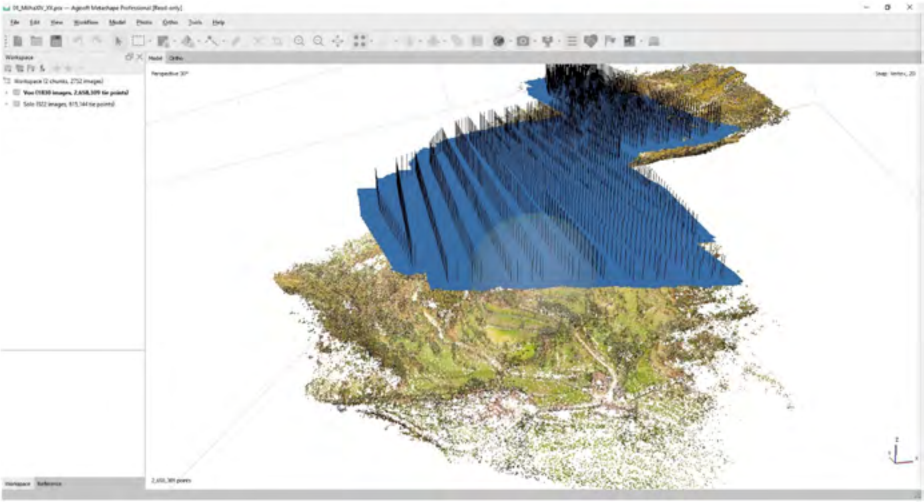

Figure 2. Survey of the *Jeira*, between the miles XIV and XV.

office, where the *Google Earth Pro* application (*version 7.3.4.8248*) was used to identify areas of archaeological significance for recording. Considering the road's span across the entirety of Terras de Bouro municipality and its considerable length, the overall area needed to be divided into manageable sub-areas. These sub-areas, ranging from 30 to 32*ha*, with perimeters between 3 and 4*km*, were defined to accommodate the capabilities of the UAV used. Each sub-area was represented by a polygon stored in *Keyhole Markup Language* (KML) format.

After finishing the processing of the route, the planning phase for the high-altitude survey began. This phase involved importing each mile segment into an automated flight management application, determining the average flight altitude, optimizing photo overlap, orienting the flight, and configuring the desired camera interaction with the UAV. Ahead of the survey, some ground control points (GCPs) were established based on the defined area segments to facilitate accurate georeferencing. It is important to note that these ground control points served the dual purpose of aiding both high-altitude and ground-level surveys.

After georeferencing each road segment, the UAV survey started. The automated mode was employed to capture the area of interest at a higher altitude, while the manual mode was used to record each mile at a lower altitude. The automated flights were parameterized with altitudes ranging

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from 50 m to 120 m, along with lateral and frontal overlap settings of 65% and 75%, respectively. Each mile survey captured a maximum of 2000 images, requiring approximately 1 hour and 15 minutes of flight time. Figure 2 provides a visual representation of the survey conducted between mile XIV and mile XV. Image processing was carried out using the *Metashape* application (*Agisoft Inc.*), utilizing photogrammetry algorithms to generate 3D surfaces and orthophotomaps.

The ground-level survey was manually executed at a minimum height of 2 meters, ensuring a consistent frontal overlap of 80%. Flying at a constant speed of 0.5 m/s and capturing each image at 2-second intervals, this survey typically produced an average of 1500 images, depending on the route's curvature, and took approximately half an hour.

With these two meshes, it is possible to create multiscale meshes that enable adaptive rendering techniques. These facilitate streaming and level-of-detail techniques, particularly useful for real-time applications such as virtual or augmented reality. Even on devices with limited computational resources, the multiscale meshes allow for efficient representation and rendering of complex 3D scenes

In addition to the road, some milestone markers and associated Roman bridges were also surveyed. The survey of the milestone markers was utilized to deepen epigraphic studies, for which a visualization methodology was developed, as outlined in Redentor et al. (2023). Surveys were conducted using a handheld scanner (*Sense 3D* Scanner) for milestone markers deposited in the Geira museum and photogrammetric surveying (*Canon EOS 550D + Canon EFS 18-55mm*) for milestone markers located in situ.

For the Roman bridges associated with the road network, surveys were conducted using a UAV and also with a conventional photographic camera (*Canon EOS 5D Mark III + Canon EF 16-35mm F2.8L II USM lens*). The 3D reconstruction of the studied elements was performed using these two sets of photographs, ensuring the dimensions and proportions of each object through control points marked on the objects of interest. These control points were recorded using a total station to ensure the accurate location and orientation of the 3D reconstruction of the artworks. The archaeological interpretation of these new data allowed for the proposal of a reconstruction model of the bridges, which is being used in a mobile application within an augmented reality context to support the visitors (see Figure 3).

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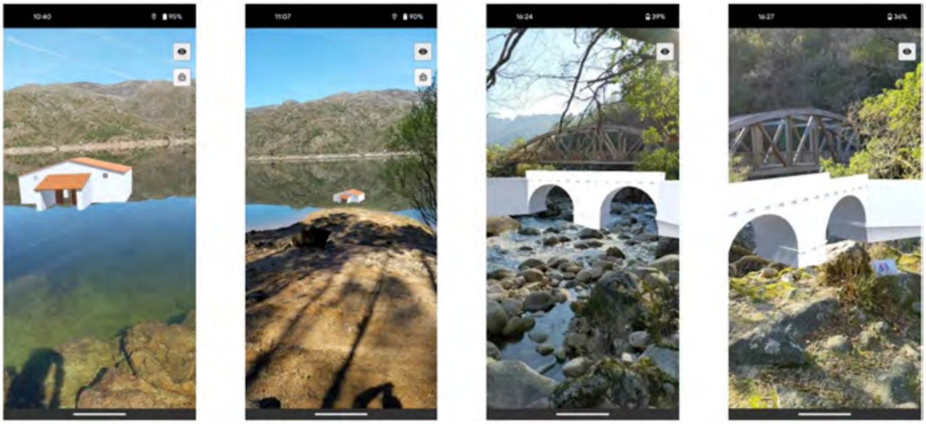

Figure 3. Mobile App with AR functionalities.

4.2. A rock art survey experience: the RARAA project

The "Open Access Rock Art Repository" (RARAA) project presents a methodology for the 3D survey of rocks with rock art motifs and the subsequent production of orthophotos from the resulting 3D models, accomplished through photogrammetry. The resulting vector graphics is integrated into a customized information system, which enhances the reuse of the data in new interpretations and research projects. The RARAA project is focused on the rock art of the Côa Valley (Vila Nova de Foz Côa, Portugal), designated as a World Heritage Site since 1998.

Various case studies demonstrate that photogrammetry is increasingly recognized as a valuable tool in rock art research (Jalandoni y May 2020; Garate et al. 2020). One of the primary benefits of photogrammetry in rock art documentation lies in its non-invasive approach, which safeguards the integrity of the artwork while delivering precise measurements and surface details.

In this project, aimed at documenting the focal rock formation covering a medium-scale area, the research team employed a versatile UAV equipped with an integrated camera featuring a *1/2.3" CMOS* sensor capable of capturing high-resolution images (*DJI Mavic Pro*). Additionally, they utilized a digital camera (*Canon EOS 6D Mark II*) equipped with a full-frame CMOS sensor boasting approximately 26.2 million effective pixels. The detailed images of the rock art incisions were captured using a macro lens (*Canon EF*

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50mm 2.5 Macro). The team responsible for the photographic survey of the rock art elements also used a mobile device (*Xiaomi - Redmi Note 9S*) associated with a stabiliser (*Zhiyun Smooth Q3*) to record images with adequate depth of field and at a short distance from the surface

To ensure accurate orientation and scaling of the 3D surfaces derived from the captured images, the team employed georeferencing of control points. This process was facilitated by using the *GPS MobileMapper 120* in conjunction with an external precision antenna (*L1/L2 GPS + Glonass, Ashtech ASH-111661*).

For the three-dimensional recording, the research team followed established photogrammetry procedures based on multiple images widely used in cultural heritage and archaeology (Marín-Buzón et al. 2021). However, given the specific nature of the site and the complexity of the elements to be recorded, it was decided to record them in two separate phases.

During the initial phase, the primary objective was to capture the entire rock formation along with each individual panel. This phase involved both photographic registration and the precise placement of control points to facilitate georeferencing, scale, and orientation of the archaeological elements of interest. To achieve a comprehensive reconstruction of the rock formation, the team captured photographs at distances ranging from 2m to 15m, ensuring thorough coverage.

In the subsequent phase, focused on capturing the intricate details of the individual panels, photographs were taken at closer distances, ranging from 1.5m to 0.5m. This approach enabled higher resolution and enhanced visibility of the panel motifs. Although our initial intention was to record images of each panel at a constant distance from the surface of interest to ensure consistent Ground Sampling Distance (GSD), the challenging terrain led to capturing each panel at different distances from the surface.

Following the generation of the initial 3D model using the previously mentioned photogrammetry techniques, it underwent a thorough optimization process aimed at ensuring accuracy and quality. This optimization addressed any gaps or holes present in the model, enhancing its completeness.

Additionally, to improve the visual appearance and surface details of the 3D model, the team employed texture mapping techniques. This involved

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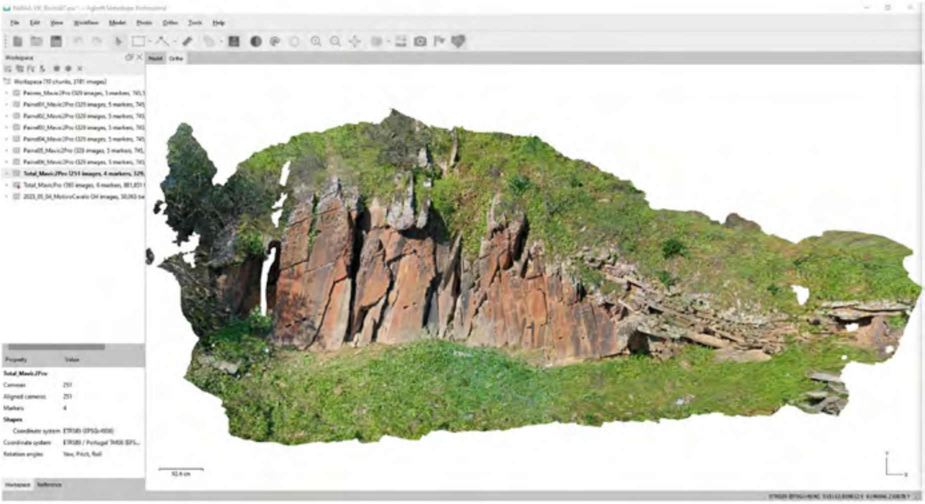

Figure 4. Orthoimage produced with Metashape (Agisoft Inc.).

overlaying high-resolution images onto the model, enriching its texture and overall visual fidelity.

The next stage of the visual representation process involves the production of orthoimages based on the textured 3D model (see Figure 4). The orthoimages are essential for facilitating the archaeological illustration of rock art motifs. During the orthoimage generation process, the detailed 3D model was projected onto a 2D plane, resulting in a flattened representation of the archaeological element. By aligning and merging individual images, the researchers generated an orthoimage that accurately depicted the completeness of the archaeological element. This meticulous process guaranteed that the orthoimage captured all pertinent details while preserving the spatial accuracy of the original 3D model.

After producing the orthoimage, a meticulous evaluation was performed to evaluate its accuracy and rectify any distortions. The focus was on precisely aligning the images and addressing any discrepancies that may have arisen during the stitching process. This rigorous procedure was crucial to guarantee that the orthoimage accurately portrayed the original archaeological element.

In the orthoimage generation process, the team took into account that the rock art was engraved onto shale rocks, which could feature planar surfaces that are not necessarily vertical. To ensure the highest accuracy in the

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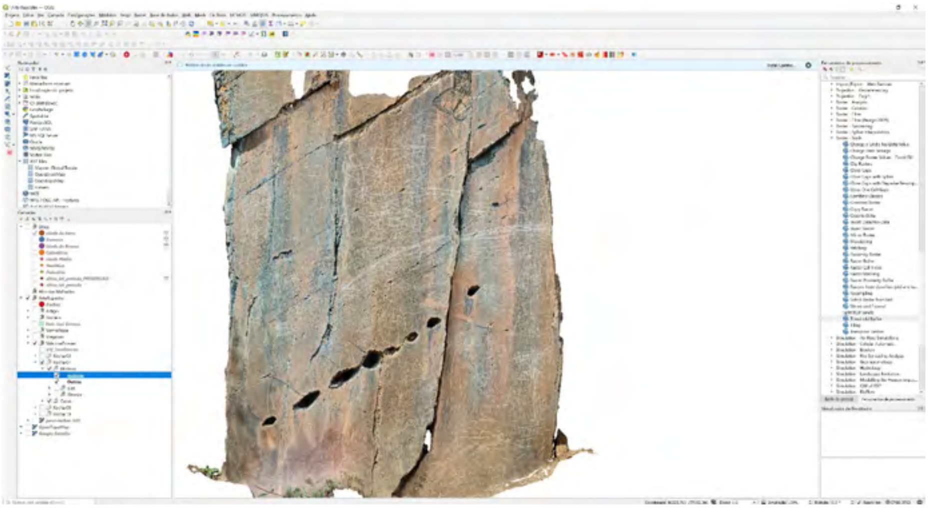

Figure 5. Processing of a panel orthoimage using QGIS.

orthoimages, the researchers devised a customized projection plane that took into consideration the inclination of each panel. Three markers were strategically placed on each panel to aid in this process, facilitating the calculation of both horizontal and vertical axes. This meticulous approach ensured the precise projection of each panel onto a plane, resulting in orthoimages of exceptional quality and accuracy.

The resulting orthoimage, depicted in Figure 5, proved to be an invaluable asset for conducting precise and accurate data analysis and interpretation of the archaeological elements (Botica, Luís y Bernardes 2023). In the realm of rock art, where visual representation is paramount, the integration of GIS is indispensable. This tool plays a pivotal role in visualizing graphical information, elucidating connections between motifs and the rock surface, and integrating data characterizing motifs.

Furthermore, GIS enhances vector data and facilitates the establishment of selection criteria for interpreting and studying art. For the implementation of the geographic information system, we selected QGIS, specifically version 3.28.3-Firenze. This software seamlessly integrates and visualizes rock art drawings, incorporating both graphic and alphanumeric data stored within the information system.

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5. Conclusion

In conclusion, the methodologies discussed offer expedient and comprehensive approaches for documenting and interpreting cultural heritage elements, preserving their intricate three-dimensional features. Through the integration of modern technologies such as photogrammetry and Geographic Information Systems (GIS), high accuracy of data collection and representation is ensured. The resulting visualizations, including orthoimages and 3D models, facilitate the comprehension of archaeological findings by both experts and the general public. Moreover, the adoption of low-cost and free/open-source solutions enhances accessibility to these methodologies, democratizing archaeological research.

The visualization of various cultural heritage elements through photogrammetry offers significant advantages for researchers. By creating precise 3D models of artefacts, monuments, and architectural structures, researchers gain invaluable insights into their spatial relationships, structural details, and historical significance. These detailed reconstructions enable thorough analysis and interpretation, facilitating the study within a broader context. Additionally, the integration of GIS data with photogrammetric models enhances researchers' ability to spatially analyse and visualize the distribution patterns of these heritage elements, contributing to a more comprehensive understanding of cultural landscapes.

Furthermore, the development of augmented reality (AR) applications for dissemination purposes enhances public engagement and understanding of archaeological sites. By overlaying digital reconstructions onto physical environments, AR apps provide immersive experiences that bring history to life, appealing to a wide audience. These interactive applications often feature virtual tours, interactive exhibits, and educational content embedded within the app, encouraging exploration and interaction with archaeological findings in their original contexts. This technology not only fosters a deeper appreciation for cultural heritage but also facilitates meaningful engagement with archaeological discoveries.

Looking forward, future endeavours in this field could explore a broader range of advancements beyond survey methods. For instance, the integration of volume rendering techniques can offer enhanced visualization capabilities, allowing for more immersive exploration of archaeological sites.

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Voxelization presents opportunities for refining the representation of objects with intricate details, further enriching our understanding of cultural artefacts. Additionally, the application of AI-driven techniques, such as deep learning, holds promise for automating data analysis tasks and extracting meaningful insights from archaeological data sets. Finally, the exploration of Neural Radiance Fields offers an innovative avenue for rendering three-dimensional scenes with unprecedented realism, opening new possibilities for digital heritage preservation and interpretation. Embracing these advancements will not only propel the field of archaeology forward but also foster a deeper appreciation and understanding of our shared cultural heritage.

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