Universidade de Aveiro
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Métodos de Representação Virtual e Visualização para Informação Arquitetónica e Contextual em Sítios Arqueológicos

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor no âmbito do Programa Doutoral conjunto em Informática das Universidades do Minho, Aveiro e Porto (MAPi), realizada sob a orientação científica do Dr.-Ing. Joaquim João Estrela Ribeiro Silvestre Madeira, Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e coorientação da Doutora Maria Manuela dos Reis Martins, Professora Catedrática do Departamento de História do Instituto de Ciências Sociais da Universidade do Minho

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Palavras-chave Representação Arqueológica 3D; Visualização Arqueológica; Métodos de Visualização; Interação 3D

Resumo Este trabalho procura esboçar algumas diretrizes no sentido de melhorar a utilização da visualização 3D aplicada aos dados arqueológicos de natureza diversa e a escalas distintas. Uma dificuldade encontrada neste processo prende-se com a, ainda frequente, representação bidimensional da realidade arqueológica tridimensional. Ciente de que a existência de dados de natureza bidimensional são fundamentais no processo arqueológico e que resultam, por um lado, dos processos manuais de registo arqueológicos e, por outro, da intensa atividade de análise e interpretação da equipa de investigação arqueológica, procuramos assegurar uma representação 3D adequada, com base em metodologias de aquisição de dados 3D geralmente disponíveis às equipas de arqueologia.
A visualização arqueológica em suporte tridimensional é uma prática cada vez mais frequente e necessária mas que continua a evidenciar algumas dificuldades. Estas substanciam-se no reduzido número de técnicas de visualização usadas, na utilização de ferramentas de visualização pouco adaptadas às necessidades arqueológicas e na utilização preferencial de características visuais dos modelos durante as fases do processo arqueológico. Assim, o objetivo primordial deste trabalho é desenhar e avaliar métodos adequados à visualização de dados arqueológicos.
Para determinar que métodos de visualização são mais utilizados durante as fases do processo arqueológico realizou-se um questionário *online* que permitiu consolidar as metodologias de representação 3D usadas, bem como propor um modelo de visualização que também categoriza as técnicas de visualização adequadas para aumentar a perceção e a compreensão visual dos elementos arqueológicos.

Definem-se três protótipos de acordo com as distintas metodologias de aquisição de dados 3D apresentados e são desenhadas metodologias de visualização que, por um lado, têm em conta a escala e a diversidade dos elementos arqueológicos e, por outro, a necessidade de assegurar métodos de visualização facilmente assimilados pelos arqueólogos. Cada protótipo foi avaliado por dois arqueólogos com experiências profissionais distintas. O que lhes foi proposto, através de um conjunto de tarefas previamente estabelecidas, foi aferir da facilidade de interação com os modelos 3D e com os métodos de visualização e adequação dos resultados de visualização às necessidades dos arqueólogos.
A avaliação dos protótipos permitiu concluir que os métodos de visua–lização apresentados aumentam a perceção dos modelos 3D que representam elementos arqueológicos. Para além disso foi possível produzir também novos objetos que revelam elementos com interesse arqueológico. É su–gerida a disponibilização destas metodologias em ambiente web e plataformas móveis.

Keywords Archaeological 3D Representation; Archaeological Visualization; Visualization Methods; 3D Interaction

Abstract This work seeks to outline some guidelines in order to improve the use of 3D visualization applied to archaeological data of diverse nature and at different scales. One difficulty found in this process is related to the still frequent two-dimensional representation of the three-dimensional archaeological reality. Aware that the existence of data of two-dimensional nature is fundamental in the archaeological process and that they result, on the one hand, from the manual archaeological recording processes and, on the other hand, from the intense analysis and interpretation activity of the archaeological investigation team, we seek to ensure an adequate 3D representation based on 3D acquisition methods mostly available to the archaeology teams.

Archaeological visualization in three-dimensional support is an increasingly frequent and necessary practice, but it continues to show some difficulties. These are substantiated in the reduced number of visualization techniques used, the use of visualization tools that are not very customized for the archaeological needs and the privileged use of visual features of the models during the archaeological process phases. Thus, the main objective of this work is to design and evaluate appropriate methods for visualizing archaeological data.

To determine which visualization methods are most used during the phases of the archaeological process, an online user-survey was carried out, which allowed consolidating the 3D representation methodologies used, as well as to propose a visualization model that also categorizes the appropriate visualization techniques which increase the visual perception and understanding of the archaeological elements.

Three prototypes are defined according to the different 3D data acquisition methodologies presented and visualization methodologies are designed in order to, on the one hand, take into account the scale and diversity of the archaeological elements and, on the other hand, to account for the need to ensure visualization methods which are easily assimilated by archaeologists. Each prototype was evaluated by two archaeologists with different professional background. They were proposed, through a set of previously determined tasks, to assess the interaction with 3D models and with the visualization methods and the satisfaction of the visualization results regarding the archaeological needs.

The evaluation of the prototypes allowed to conclude that the presented visualization methods increase the perception of 3D models which represent archaeological elements. In addition, it was also possible to produce new objects that reveal elements of archaeological interest. It is suggested to make these methodologies available on a web-based application and on mobile platforms.

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Chapter 1

Introduction

The archaeological process produces and manipulates data of distinct nature and of high complexity. Particularly with regard to three-dimensional data, the proper use of 3D data acquisition techniques and 3D reconstruction methods is an exceptionally demanding challenge. *Image-based 3D acquisition*, *Computer Graphics*, *Geometric modelling* and *Visualization* methods and techniques are certainly a response to this challenge and have been progressively used, over the last years, to represent and visualize archaeological data, both for experts or general public [1][2].

1.1 Motivation

The archaeological excavation remains a fundamental process for collecting data from sites despite the growing importance of non-destructive exploration methods [3]. Although it is an irretrievable destructive method, its purpose is not restricted to unveil successive sediment layers, findings and structures, but to record data and produce graphical and written documents of every finding. Such documentation will be used to understand how the site was transformed over the years and study the different layers and findings, to establish eventual relations between them, and to understand the global human occupation of the archaeological site [4].

The dissemination of archaeological sites, as well as of that of archaeological finds or objects, is increasingly performed by virtual 3D models which are effective instruments of the archaeological discourse. Hypothetical models representing a virtual reconstruction of archaeological elements can be accessed through digital platforms that range from simple multimedia kiosks to complex augmented reality systems. The purpose of these 3D representations is, generally, to present research results to a wider and heterogeneous audience. But, further significant, such virtual 3D models can also be used as an auxiliary tool for archaeological research [5][6].

The virtual models can be obtained either by 3D modelling techniques or by image-based modelling procedures. In the first case, it is possible to set up a scene that is a cognitive model of the Past, resulting from the archaeological analysis and interpretation. In fact, a model of an archaeological element that has been conceived according to an interpretation of the archaeological data is a representation of what, for some reason, has been destroyed or is in a unacceptable state of conservation but can be regarded as a virtual digital mockup that might be disassembled to improve the analysis and understanding of the architectural structures, the way they relate with each other and their relationship with the surrounding space [7]. The second method, based on digital photographs, generates a representation of visible archaeological elements. This modelling procedure creates a 3D surface that might be considered a digital surrogate if it has the necessary quality and accuracy to substitute the original. Therefore, it can be used to disseminate the existing archaeological elements and, if the required precision is ensured, for analysis and interpretation purposes [8].

Naturally, it is also possible to represent a virtual model from the data of non-intrusive survey. Particularly interesting are the geophysical surveys that simultaneously record the spatial data and scalar values (usually representing physical properties) which are associated with subsurface features. Its three-dimensional representation allows not only the generation of a visual model of what is not seen but also the analysis and interpretation of the physical properties that may refer to subsurface volumes with potential archaeological significance.

The nature of the archaeological data is considerably heterogeneous to ensure the suitable representation of (1) what might have existed but is no longer available, (2) what currently exists and is visible and (3) what possibly exists but is not visible. Establishing adequate 3D representation methodologies and visualization procedures capable of getting more insight and understanding from the data of these different representations are highly motivating tasks to accomplish.

1.2 Problem statement

The concept of *archaeological visualization* is often restricted to purely "empirical" and/or realistic visualizations that emulate reality or that display data in traditionally long-lasting ways [9]. There is seldom concern about the best strategies to display or visually explore archaeological information, or to present alternative ways to present data, its merits and limitations.

Llobera (2011) argues that the most familiar type of visualization in Archaeology is the *scientific visualization* since it refers to various techniques used to represent, explore and interpret data derived from observations and models [9]. The objective is to gain insight into the data and the underlying processes that generate them. However, although the wide-ranging and well-established techniques that are currently in use in scientific visualization, very few have been adopted by archaeologists, mainly because:

- Archaeologists constantly alternate between different conceptualizations of space;
- The exhaustive level of sampling needed for scientific visualization is not frequently achieved in Archaeology;
- For the most part, archaeologists concern themselves with collecting simple information that can be adequately displayed using basic symbols and colour.

Meyer et al. (2007) consider that the use of computer science in Archaeology is often driven by what the software offers, instead of being determined by archaeological questions [10]. Regarding archaeological visualization, in most cases, it is a matter of applying existing visualization software [9]. In fact, the purpose of visualization in archaeology is largely simplified to a question of illustration and/or digital archiving. Naturally, this purpose is not a minor issue and brings great advantages to the way archaeological information is managed. However, a key role that visualization methods can play in the archaeological process is in providing interfaces to data sources that help to identify uncertainty and enable the exploration of alternative interpretations. Therefore, there is currently a major concern in developing customizable 3D visualization platforms, usually based on specific visualization libraries, to face archaeological problems [11].

The visualization of archaeological data is mainly applied during three steps of the archaeological process: (1) *analysis of the archaeological data*, (2) *interpretation of the archaeological data* and (3) *dissemination of the results*. However, data visualization during the *archaeological survey* is exceptionally useful to an archaeological team. In fact, when visualizing the surveyed data, archaeologists will be capable to interact with a 3D model as it would be a detailed and accurate 3D photograph. However, if the 3D model is only used as "enhanced" images, the archaeologists fail to take advantage of the improved characteristics of the 3D representation of the site [12].

Despite the advances and enormous significance of computer-supported visualization techniques applied to archaeological data, there are still important difficulties that justify our attention. This work will focus on contributing to the resolution of some difficulties presented in the previous paragraphs and which can be stated as follows:

- Only the advantages of a reduced number of visualization techniques are used;
- The visualization tools are, generally, not customized for archaeological necessities;
- Normally, only the visual features of the 3D model are used for archaeological analysis.

1.3 Research questions

Computer-supported visualization procedures incorporate significant techniques that, if applied to Archaeology, most certainly improve the perception and insight of archaeological data. However, the introduction of new visualization techniques into the archaeological process might disturb the consolidated traditional visualization workflow for archaeological elements. Some of these difficulties were presented in the previous section and raise the following research questions which this work will try to answer:

- What is required to successfully use more visualization techniques in archaeological visualization?
- How can visualization techniques be used to improve the visualization tools according to the archaeological needs?
- What kind of visualization procedures can be used to increase the usage of the 3D model features?

These three research questions emerge a hypothesis that will be tested in this work:

- The use of computer-based visualization and interaction techniques, grounded on procedures inherent to the archaeological practice, can contribute to the increase of perception and insight on archaeological data that represent realities that have existed (but are no longer available), existing and visible realities and existing but not visible realities.

1.4 Objectives

The aim of this work is to design and evaluate methods to appropriately represent and visualize architectural and contextual information in archaeological sites and procedures to interact with the 3D models. The proposed system has to interact equally with the data from archaeological excavation, as well as with possible reconstructions of an archaeological site. This aim comprises two main objectives:

- The development of realistic visual representations of an archaeological site is the first objective because Archaeology relies on accurate (or at least as accurate as possible) models to disseminate the knowledge about a site both to the scientific community and to the non-experts;

- The non-photorealistic representation of the archaeological data for knowledge discovery purposes and to simplify the overall representation of a site.

The evaluation of all the virtual representation and visualization methods and of the suggested 3D interaction procedures will be performed on virtual models of archaeological elements closely connected to archaeological work carried out by the *Archaeological Unit of the University of Minho*.

1.5 Published work

The work presented in this thesis resulted in the following peer-reviewed publications:

- Paulo Bernardes, Joaquim Madeira, Manuela Martins, José Meireles, "The use of traditional and computer-based Visualization in Archaeology: a user survey", Proc. VAST 2012: The 13th International Symposium on Virtual Reality, Archaeology and Cultural Heritage, Brighton, UK, 19 – 21 November 2012.

- Luis Sebastian, Paulo Bernardes, “Reconstituição arquitectónica do claustro medieval do mosteiro cisterciense de São João de Tarouca (Viseu, Portugal)”, Proc. International Conference on Cloisters in the Mediterranean World (10-18th c.), Lisbon, Portugal, 10 – 22 June 2013.

- Paulo Bernardes, Fernanda Magalhães, Jorge Ribeiro, Joaquim Madeira, Manuela Martins, “Image-based 3D modelling in Archaeology: application and evaluation”, Proc. WSCG 2014: The 22nd International Conference on Computer Graphics, Visualization and Computer Vision, Pilsen, Czech Republic, 2 – 5 June 2014.

- Mafalda Alves, Paulo Bernardes, Luís Fontes, Manuela Martins, Joaquim Madeira, “Feature enhancement from electrical resistivity data in an archaeological survey: the Sapelos hillfort experiment (Boticas, Portugal)”, Proc. SPIE 9535 RSCy 2015: Third International Conference on Remote Sensing and Geoinformation Environment, 95350T, Paphos, Cyprus, 16 – 19 March 2015.

- Paulo Bernardes, Natália Botica, Fernanda Magalhães, Manuela Martins, “Uma Plataforma de Representação e Divulgação da História Urbana de Braga”, Proc. 3 Congreso Internacional de Arqueoloxia de Vilalba, Vilalba (Lugo), Spain, 20 – 23 July 2015.

- Natália Botica, Paulo Bernardes, Manuela Martins, Joaquim Madeira, “Digital media as an effective platform to archaeological data dissemination”, Extended Abstract Proc. 22nd Annual Meeting of the European Association of Archaeologists, Vilnius University - Faculties of History, Philology and Philosophy, Vilnius, Lithuania, 31 August - 4 September 2016.

- Paulo Bernardes, Natália Botica, Manuela Martins, Joaquim Madeira, “The virtual model paradigma in the analysis and dissemination of ancient urban facilities”, Extended Abstract Proc. Lost and Transformed Cities: a digital perspective, Faculty of Social Sciences and Humanities, Nova University of Lisbon, Lisbon, Portugal, 17 – 18 November 2016.

- Paulo Bernardes, Bruno Pereira, Mafalda Alves, Luís Fontes, Andreia Sousa, Manuela Martins, Fernanda Magalhães, Mário Pimenta, “Under the pile. Understanding subsurface dynamics of historical cities through geophysical models interpretation”, Extended

Abstract Proc. European Geosciences Union General Assembly 2017 session "From Artefact to Historical Site: Geoscience and Non-Invasive Methods for the Study and Conservation of Cultural Heritage", Vienna, Austria, 23 – 28 April 2017.

- Paulo Bernardes, Mafalda Alves, Bruno Pereira, Joaquim Madeira, Manuela Martins, Luís Fontes, "Visualization of ERT Data for Archaeological Purposes", Proc. EUROGRAPHICS Workshop on Graphics and Cultural Heritage, Graz, Austria, 27 – 29 September 2017.

1.6 Document structure

This document is structured in eight different chapters, starting with a brief introduction where the motivation, the problem statement and the research questions of this work are presented. This first chapter is followed by a chapter where the digital technologies used in Archaeology are presented. It starts with a short explanation about the archaeological process and to what extent computer applications and 3D acquisition techniques are used in the archaeological daily practice. Also, it refers to the principles that should guide computer applications in heritage and archaeological context. These principles alert to the conditions in which computer-based applications should be used. At the end, the chapter describes different 3D acquisition and representation methods frequently used in Archaeology.

Since this work is about visualizing archaeological data, the third chapter begins with a resumed definition of visualization and its importance over the centuries. Later it explains the influence of visualization in Archaeology, the main visualization strategies used when visualizing Heritage and how computer-assisted archaeological visualization has evolved over the last decades. At the end of the chapter, it is also clarified which visualization strategies will be used in this work.

The fourth chapter is about evaluating the visualization procedures used during the archaeological process. This assessment is realized with the help of a user survey that was distributed by e-mail all over Europe. It describes the design of the user survey and how the responses where validated and analysed. The results are thoroughly presented regarding the use of traditional and computer-based visualization tools in the archaeological process. The results of the survey also compare the archaeologists' preference regarding realistic and non-realistic visualization methods.

The subsequent chapter defines the visualization model applied to the archaeological data which are used in this work. Three visualization levels are proposed that enable increasingly more visual perception and insight into the data. The second section of this chapter also specifies and describes the 3D acquisition methodologies of the used data.

The sixth chapter is entirely dedicated to describe the visualization methods which are used in the three prototypes. Each prototype corresponds to a distinct data acquisition methodology and the visualization methodologies are based on the traditional practices for representing and visualizing archaeological data. Each visualization method is associated with a specific level of the visualization model and used in at least one of the prototypes.

The seventh chapter is entirely devoted to the evaluation of the three prototypes, regarding the usability and the capability to produce new understanding about an archaeological element. Each prototype was assigned specific tasks that were carried out by experts. The prototypes were evaluated with archaeological data recorded at different sites of different nature and located in Braga and Boticas (northwest and northeast of Portugal, respectively).

The last chapter presents the global conclusions of the work carried out and recommends some ideas for future work. The end of the document includes also an appendix with the complete structure of the user survey discussed in chapter 4.

Chapter 2

Digital technologies in Archaeology

In Archaeology, the methodologies used during the record, analysis, research and dissemination phases resort to different areas of knowledge and, whenever possible, keep up with the technological evolution. The use of computer applications, which have been introduced in Archaeology during the late fifties (Europe) and early sixties (North America) of the last century [13], is particularly relevant. The main purpose of those computer projects was not only to analyse and classify different findings but also, as explained in *Chenhall* (1968) [14], to prove the utility of the computer as a tool in archaeological research.

In just a few years the number of computer applications in Archaeology grew in an exponential way, so that in the early seventies the computer was adopted as a major tool for research purposes. At that time, the computer applications main areas were the *descriptive statistics and data organization*, the *seriation*, the *classification and multidimensional scaling* and the *databases* [15].

Later, with the considerable advances of computer graphics and 3D modelling techniques, a major concern was to create 3D representations of archaeological elements, which could either be archaeological artefacts [16], sites [17][18] or landscapes [19]. This 3D representation was not only important for the objectives of archaeological research [20][[21], but also for dissemination of its results [22], as can be assessed from numerous published works. By the end of the last century, the influence of computer-based data processing to assist archaeological matters was extremely noticeable, particularly in areas such as *databases*, *geographical information systems* (*GIS*), *visualisation* and even *artificial intelligence*. The emergence of international conferences and journals where computer-assisted archaeology held a central role confirmed this growing influence [23].

At the moment we are not only witnessing a considerable intensification of computer application projects in Archaeology but also an incredible growth of computer application areas used and/or developed for archaeological purposes. The initial computer application areas in archaeology are still extremely important for the archaeological process, but areas such as artificial neural networks, computer vision, virtual and augmented reality, serious gaming, 3D acquisition and interaction are also gaining a developing significance in archaeology. This can be assessed by the excellent research published in journals of reference 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 or the *Virtual Archaeology Review*, among others, or presented in conferences such as the *Computer Applications and Quantitive Methods in Archaeology* (*CAA*), the *International Meeting on Archaeology and Graphic Informatics, Cultural Heritage and Innovation* or the *EUROGRAPHICS Workshop on Graphics and Cultural Heritage* (*EG-GCH*).

The potential of computer applications and technology in Archaeology were simultaneously recognized by different research groups all over the world and, therefore, diverse expressions to describe this effort have appeared. The most common are *Virtual Archaeology* [24], *Digital Archaeology* [25] and *Cyber-Archaeology* [26].

The term *Virtual Archaeology* was used for the first time by Paul Reilly to express something that can act as a surrogate of an original archaeological element. His initial concept was based on the assumptions that using the archaeological record combined with technologies such as hypertext, multimedia and 3D solid modelling would create an accurate recreation of an archaeological site. Afterwards, the concept expanded and covered the application of visualization and presentation methods to the virtual representation of past environments which include buildings, landscapes and artefacts [27]. This means that the focus of *Virtual Archaeology* is mostly visual, graphic and representational.

Digital Archaeology is about understanding the strengths and weaknesses of computers and information technology to the best advantage of Archaeology. Therefore, it explores the potential of information and communication technology to expand the limits of archaeological theory and practice for better recovering, understanding and presenting the past [28].

Cyber-Archeology is not so much concerned with the reconstruction of the past, but essentially with the simulation of the past [26]. Therefore, it is not necessarily visual nor oriented to photorealism, but entirely 3D, dynamic, interactive and complex. Cyber-archaeology is very much focused on collaborative environments, collaborative research and virtual models to create a potential past.

Although the expressions are not similar, the aims and activities are very comparable [29]. The figure 2.1 represents the simple workflow of computer-assisted archaeology, both for visible and non-visible archaeological data. After performing the 3D acquisition of the archaeological data, it is necessary implement a visual 3D representation of the archaeological elements. These elements are used by the archaeologist either for research or dissemination purposes. The 3D representation of the archaeological elements might be improved and occasionally even the 3D acquisition has to be complemented during the research and interpretation phase.

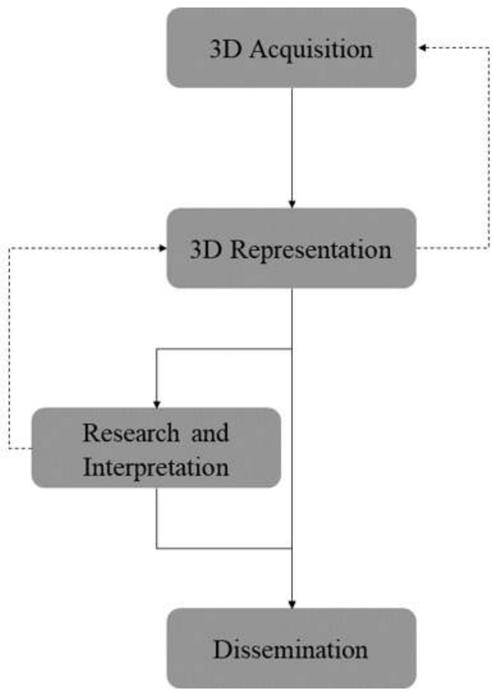


Figure 2.1: Computer-assisted workflow in Archaeology

This chapter will explain what the archaeological process consists of and how computer applications and 3D data acquisition techniques are used in the daily archaeological practice to produce a reliable archaeological record that always enables a three-dimensional representation of an archaeological site. The principles that should guide the use of computer-based applications in Heritage are also presented because any intervention in cultural assets must comply with strict principles that guarantee its conservation and preservation. Later in this chapter, the author also refers to the different methods of acquisition and 3D representation used in the context of the archaeological process and at the end, some reference projects of computer application in archaeology are mentioned.

2.1 The Archaeological Process

As referred to in *Martínez* (2000) [30], Archaeology is a science that uses other disciplines to ensure the validity of archaeological data and to assess an increasingly rigorous theoretical reasoning. In fact, the work of the archaeologist is, according to some authors, comparable to the work of an engineer. For an engineer, each project is a new problem. In a similar way, for an archaeologist, each excavation is a new challenge. Indeed, the creative capacities to apply general principles to specific situations that have never been seen before, in order to record as much information as possible (in spite of some technical and financial difficulties), are the qualities that best define an archaeologist in the field.

The main objective of the archaeologists' work is to rebuild, for each site, the complete process that led to the establishment of the archaeological record [30]. That is, it is necessary to understand how the site and structures were built and how (and why) they were abandoned, destroyed and covered by distinct and successive layers of deposits. As explained in [31], understanding the mechanisms of the creation of archaeological sites is the key to their interpretation and, consequently, to their reconstruction.

To achieve these purposes, the archaeologist has the precious help of the archaeological survey and excavation.

2.1.1 Archaeological Survey

The archaeological survey covers the field work and the laboratory work that precedes the excavation ([30], [32]). The field work includes a careful study of the geographical area in order to discover the largest possible number of archaeological evidence in the landscape. The laboratory work is mostly responsible for analysing the prior information that exists about the area of interest. This information is distributed in several different documentary sources, such as topographic maps, aerial photographs and written documentation.

For survey purposes, it is essential to understand the topographic maps related to the geographical areas of interest, not least because it is an aid for archaeologists to correctly locate an archaeological site [32]. But the correct interpretation of the maps is also useful to identify the characteristics of the terrain and to recognize structures of buildings, partially or totally, in ruins. The maps are also valuable to determine which areas are most interesting for analysis. Also important is the scale of each map, which might emphasize different aspects of the terrain. Sometimes, it is also significant to compare maps of the same area but from distinct time periods to search for characteristics that have changed or evolved over time.

Another helpful tool for the archaeological survey is aerial photography. The advantage of using this tool is to discover buried archaeological structures that are generally more noticeable from the air, because (1) the shadows of the protruded structures enhance their visibility, (2) the differentiated growth of the crops and the various levels of humidity are strong indicators of the existence of buried structures and (3) the existence of diverse coloured objects might represent structures that were revealed during the tilling of the land [32]. Besides the discovery of possible archaeological structures, aerial photographs are also important to provide additional information about the topology and vegetation of the terrain.

Also, both the geophysical survey and phosphate analysis are frequently used in the archaeological survey [30]. The first method measures certain electrical and magnetic properties of the subsoil which might reveal the location of buried structures. The chemical analyses of phosphates within an area of interest indicate the diverse human activities in that area.

2.1.2 Archaeological Excavation

According to [32], an archaeological excavation comprises two approaches: (1) the exposure of vertical sequences of deposits that reflect the long-term occupation of a site and (2) the recovery of horizontal plans of individual features or particular periods of occupation. Excavating an archaeological site remains one of the main techniques used to collect a wide and accurate panel of data from the site's depositional contexts. The interpretation of the recorded data operates at different scales, related to the scientific problem, which is also determinant for adding a multidisciplinary approach to analysis. Figure 2.2 shows the different stages of the archaeological work, from the excavation to the dissemination of results.

Another fundamental purpose of an archaeological excavation is to understand how the site was used and transformed through the years since this will explain the origin of the different sediment layers. Ideally, after concluding and archaeological excavation it should be possible to represent the site, placing all elements in its original location, based on the archaeological record [30]. Consequently, the stratigraphic observations have to be registered in the traditional section drawings. To improve the readability and interpretation of a stratigraphic sequence the archaeologists use the Harris Matrix [33]. The Harris Matrix brought great benefits to the study of stratigraphy because it summarises complex sequences in diagrams, which are then easier to understand.

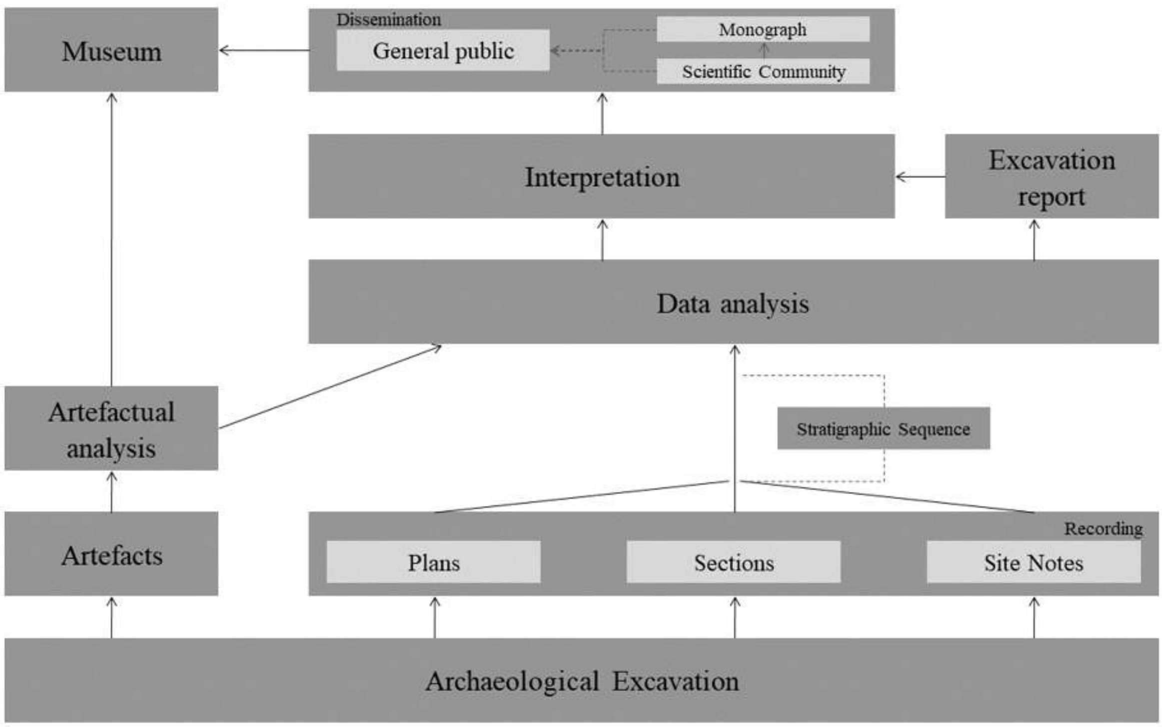


Figure 2.2: Different steps of the archaeological process

An extremely important characteristic of the excavation is the archaeological record. The increasing demand for objectivity and accuracy, combined with the growing complexity of large excavations (particular those in urban environments) led to the design of forms used for standardised recording purposes [32]. These forms are used to describe the position, size and characteristics of each separate excavated unit and also to record its relationships with all adjacent units. Usually, they are designed in a way that allows data to be entered rapidly into an archaeological information system. The archaeological information system contains also other data such as vector data from the digitized plans and section drawings, raster data such as photos (from excavation units and from artefacts) and artefact drawings, videos and 3D data. Later on, all this data might be analysed and interpreted using *GIS* techniques [28].

An excellent way to increase the comprehension of an archaeological site is to create a scale model or, using archaeological illustration, a reconstruction drawing. If the purpose is to recreate a building, the information about foundations, pillars, walls or other architectural structures is particularly helpful. No less important is the comparison with surviving structures and documentary evidence. The careful analysis of the data might produce new interpretations which possibly suggest different reasonable reconstructions that can be easily accomplished using computer-based reconstructions [28].

2.2 Principles of Computer-based applications in Heritage

The awareness about the importance of Heritage is an important value, that has always been sought to transmit to future generations. The particular consciousness that an archaeological excavation is always a destruction [31], justifies the constant concern of the archaeological community to regulate interventions at a site. Since the beginning of the twentieth century, we have seen the formulation of some documents that set important guiding principles in terms of conservation and preservation of heritage.

After the second half of the twentieth century, some of these principles are already concerned with computer-based use in heritage and archaeological context. In particular, these principles determine in which circumstances and to what extent computer-based applications should be used and which computer-based technologies and methods are adequate to be used. The most accepted guidelines are assembled in four distinct documents:

- *Principles for the Conservation and Restoration of Build Heritage*;
- *ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites*;
- *International Charter for the computer-based visualization of Cultural Heritage*;
- *International Principles of Virtual Archaeology.*

2.2.1 Principles for the Conservation and Restoration of Built Heritage

The *Principles for the Conservation and Restoration of Built Heritage* (*The Charter of Krakow 2000*) [34], were formulated by the participants of the *International Conference on Conservation "Krakow 2000"* as a guideline for the efforts to safeguard cultural heritage. The *Krakow Charter* follows the spirit of the previous principles (*Charter of Venice* – 1964) but adjusted to the reality of the turn of the century.

In one of its articles, the authors recommend that modern technologies, databases, information systems and virtual environments should be used for the protection and public presentation of archaeological sites. This suggests that computer-based applications should be used as an alternative to access physical restricted sites and to present the archaeological information to a wider public. This charter has the first reference to the use of computer-based tools in heritage.

2.2.2 ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites

This charter was defined in 2008 by the *International Council on Monuments and Sites* (*ICOMOS*), an international professional association that is concerned with the conservation ethics and protection of cultural heritage sites all over the world, and it is known as the *Ename Charter*. The aim of this charter was to define the basic principles of interpretation and presentation both for heritage conservation efforts and to enhance public understanding of heritage sites.

The *Ename Charter* recommends that virtual reconstructions should be based upon evidence gathered from the archaeological, architectonic and historical data and having also in consideration written, oral and iconographic sources and photography. It also stresses out the importance of alternative reconstructions, based on the same information sources, for comparison purposes [35].

2.2.3 International Charter for the computer-based visualization of Cultural Heritage

The *International Charter for the computer-based visualization of Cultural Heritage* (*London Charter*) was the first document entirely dedicated to defining the guidelines of computer-based visualization in cultural heritage [36]. This charter was defined in 2009 and it is concerned with the research and dissemination of heritage not only within the academic and educational world but also between the entertainment industry and commercial domain.

The London Charter is based on 6 principles which were defined to confirm the trustworthy of digital visualization methods in heritage, to ensure the rigorousness of the status of knowledge that these digital visualizations represent and to reflect the clear distinction between evidence and hypothesis. These principles are:

- *Implementation* — each community of practice that deals with heritage research and dissemination should develop implementation guidelines within the spirit of the London Charter and based on the institutions aims, objectives and adopted communication methods. These guidelines are encouraged to be followed by all collaborators and they should be aware of the principles of the London Charter.

- *Aims and Methods* — computer-based visualization methods should be only used when it is effectively the most appropriate visualization method, therefore it is not to be assumed that it is proper for all cultural heritage research and communication aims. Although it is not always a unanimous task, for each aim it is indispensable to evaluate which computer-based visualization method is suitable.

- *Research Source* — research sources are all information (digital or not) that are considered or that influence computer-based visualization results. Therefore, research sources should be carefully identified and evaluated to ensure the integrity of the computer-based visualization methods and its results.

- *Documentation* — necessary information should be documented and disseminated to allow the understanding and evaluation of the visualization methods and results. Some documentation strategies should be implemented and supported to enhance the visualization activity and to allow rigorous and comparative analysis of computer-based visualizations. The documentation should also include the reason why computer-based visualization is chosen to the detriment of other methods. Also, the decisions that took place during the computer-based visualization process have to be documented in order to later understand the relation between the visualization results and the research sources.

- *Sustainability* — strategies should be planned to define the most reliable and sustainable form for archiving computer-based visualization results. Digital preservation of the computer-based visualization data is important to enabling their use in the future. If digital archiving is not possible, a two-dimensional record is better than a total absence of a record.

- *Access* — computer-based visualization projects for cultural heritage purposes should be planned to enhance its access or because the object of interest has been lost, destroyed or changed. These projects should also implement different type or degrees of access, depending on the users, particularly what concerns the manipulation and modification of the object.

Despite the recognized importance of the *London Charter*, it concerns to heritage in a more global way, so that the implementation of guidelines for archaeological purposes was immediately considered a fundamental task [37].

2.2.4 International Principles of Virtual Archaeology

The *International Forum of Virtual Archaeology* established, in 2011, the *International Principles of Virtual Archaeology* (*Sevilla Charter*) to develop the implementation of the *London Charter* regarding Archaeology [38]. The objectives of this charter include the establishment of criteria to measure the quality of the computer-based visualization projects in archaeology, the responsible use of new technologies to enhance the archaeological heritage management and to improve and transform the research, conservation and dissemination of archaeological heritage. The principles of the *Seville Charter* are:

- *Interdisciplinarity* — computer-based visualization projects, associated with archaeological heritage, have to be supported by a team where the members have a different scientific and technical background. It is important to ensure the presence of the scientific management responsible for the archaeological intervention.

- *Purpose* — before starting any computer-based visualization procedure the team has to undoubtedly define the goal of the work, which is, usually, to improve aspects related to research, conservation or dissemination. Sometimes it is important to define different levels of detail, resolutions and accuracies to obtain more precise knowledge about the problems to be solved. Computer-based visualization must be at the service of archaeological heritage and not the opposite.

- *Complementarity* — computer-based visualizations should not replace the more traditional methods but rather search for collaborations to improve the archaeological research, conservation and dissemination.

- *Authenticity* — archaeology is not an exact or irrefutable science, therefore it must be always possible to distinguish what is real from what is not when using computer-based visualization. The virtual representations have to show clearly the different levels of authenticity. Computer-based visualization must help the experts and the public to undoubtedly recognize the origin of the visualized data.

- *Historical rigour* — any computer-based representation must be supported by rigorous research and historical and archaeological documentation. The virtual reconstruction has to represent all historical phases of the site, not only the time of glory but also the periods of deterioration. The accuracy of the archaeological recording is extremely important. Therefore, the new techniques such as photogrammetry or laser scanners should be used whenever possible to increase the quality of the scientific documentation.

- *Efficency* — before starting a computer-based visualization project it is essential to understand the economic and technological needs of the project. The priority should be given to systems with long-term profit, minimum maintenance and high reliability. Also, the re-use of previous results is significant for efficiency purposes.

- *Scientific transparency* — computer-based visualization projects have to be testable by other researchers to ensure the validity of the projects conclusions. Therefore, each project has to be carefully documented regarding its objectives, methodology, techniques, reasoning, origin and characteristics of the sources of research, results and conclusions. It is also extremely important to promote the publication of the results in scientific journals and books to be accessed predominantly by the scientific community.

- *Training and evaluation* — computer-based visualization projects are planned to help the general public and the archaeological research and conservation community. In the case of the expert community, the evaluation method is a test performed by a representative number of users. For the general public, the evaluation of such projects should be done with visitors studies. The quality of the project should be assessed based on the rigour and not necessarily on the spectacularity of the results.

2.3 Digital Data Acquisition Techniques

The major interest of the scientific community, regarding 3D digitizing techniques in cultural heritage, are the particular requirements of conservation and record. However, *Pieraccini et al.* (2001) [39] suggest other application fields such as:

- *Digital archives of 3D models* — the traditional archiving methods, which include manual drawing and photographs from various angles, are particular slow, time-consuming and present a number of evident limitations. A digital archive of high quality 3D models is a great improvement in this field, because they can be used as reference for degradation monitoring and restoration of artefacts.

- *High fidelity physical replica of artworks* — frequently, artworks in the open air must be substituted by copies and museums must also replicate artworks, both for archiving and merchandising purposes. A 3D model would enable more accurate replica operations and also simplify these operations and make them cheaper.

- *Remote fruition of cultural heritage* — digital 3D models offer new and very interesting teaching and research facilities since they avoid long trips required to access a small number of artworks and also enable access to unreachable sites.

- *Digital restoration* — computer graphics tools can be used to virtually restore the damaged parts of an artwork, creating 3D models with its original aspect.

- *Monitoring of cultural heritage* — the monuments in an open environment are continuously and, sometimes, irreversible damaged. Frequently, these damages are detected too late. Accurate digital acquisitions, at regular times, could detect small deformations and facilitate rapid interventions.

Not a very long time ago, the indispensable and affordable tools for the archaeological record were paper, pencil, ruler, compass, protractor, measuring tape and level. Also important, but not so affordable, were the analogue camera and the total station. Although occasionally with some resistance to change, this setting has improved over the last two decades, due to the undeniable benefits of the digital recording techniques. The advantages of digitizing cultural heritage items and, in particular, archaeological heritage are exhaustively presented in *Pieraccini et al.* (2001) [39] and *López et al.* (2003) [40], respectively.

Each archaeological project has very specific challenges regarding the recording procedures. Some of them have to deal with a variety of elements that range from very small objects to enormous structures. Therefore, digital data acquisition techniques have to deal with different scales that are needed for archaeological research:

- *the territorial scale* – to record the topography of the landscape with archaeological interest and to discover archaeological features;
- *the archaeological site scale* – to record everything that is associated with each archaeological site, such as architectonic structures and the excavated areas;
- *the archaeological object scale* – to record artefacts and excavated finds.

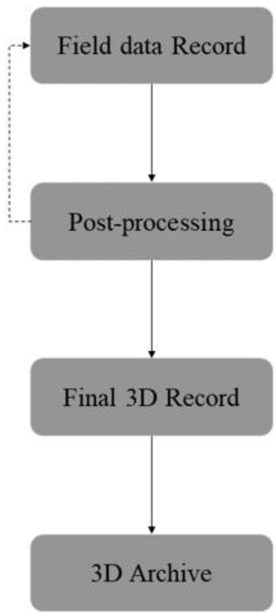


Figure 2.3: 3D acquisition workflow in Archaeology

Besides the constraint of the objects scale, often these archaeological elements have to be documented under challenging weather conditions, at locations with difficult access or in the middle of nowhere. This encompasses some restrictions and conditions to the acquisition techniques and the devices used in archaeological projects. Figure 2.3 illustrates the general 3D acquisition procedure in archaeological projects. After recording the field data, the next task is to analyse the completeness and accuracy of the data in the post-processing step. Once the completeness and accuracy of the recorded data are ensured, the subsequent step is to produce the final 3D point cloud which will be stored in a 3D archive.

2.3.1 Recording the Visible

The importance of accuracy during an archaeological record is unquestionable. Therefore, archaeology teams have to use devices that, for every situation, give them the confidence to reach the required rigour. Also, it is important to remember that an archaeological site is a three-dimensional reality, and so the acquisition methodology should ensure 3D reproducibility.

Currently, there are numerous 3D acquisition options with different levels of accuracy and which are appropriate for archaeological purposes. Naturally, the scale of the archaeological elements conditions the choice of the 3D acquisition devices, which are based on distinct technologies. The most common are:

- *Laser triangulation* – based on a laser source and an optical detector. The laser source emits light on the surface of the objects, which is reflected, by an angle α, on the optical detector (usually a digital camera) that enables the estimation of the height from the laser to the surface point. This procedure is repeated over the entire surface of an object, originating a dense and extremely accurate point cloud.

- *Time-of-flight Laser* – based on finding the distance of a surface by timing the round-trip time of a pulse of light. The accuracy of this system is not so high; however, it is adequate to capture 3D information of large scenes in a fast way.

- *Structured light* – based on the projection of a specific predefined light pattern on the surface of the objects. This scene is captured by a normal digital image detector and processed to calculate the geometry from the deformations of the pattern in the digital image. Generally, it is a portable and simple-to-use system that achieves impressive results in terms of accuracy and productivity.

- *Stereo-photogrammetry* – based on the same principle as the human vision system. The acquisition of 3D models is based on 2D images collected from different view angles. It is a very simple and inexpensive technique used for 3D acquisition; however, the accuracy is not very high.

According to *Pavlidis et al.* (2007) [41], the complete digital recording of Heritage is a multidimensional process that addresses not only the problem of 3D digitization of objects and monuments but also aspects related with the digital content management, representation and reproduction. Therefore, the authors suggest several possible parameters that determine the choice of an appropriate 3D digitization technique for cultural heritage applications, which, to some extent, is a refinement of the 3D acquisition requirements presented in *Pieraccini et al.* (2001) [39].The most significant parameters to be analysed are the ones related to the object to be digitized. These parameters are basically the material and the size of the object.

Also important are the hardware and software features of the 3D acquisition system, such as the accuracy of the system, the portability of the equipment, the compliance of the produced data with standards, the productivity of the 3D acquisition technique used and the texture acquisition capability. There are also parameters that are neither related with the object to be digitized nor with the 3D acquisition system but have to be taken in account: (1) the skill to handle the equipment and (2) the cost of the equipment.

Figure 2.4: *ALS* system example (LiDAR sensor mounted on an *unmanned aerial vehicle*)

Archaeologists seek to use laser equipment whenever their project budget allows. So, for the territorial scale, there is a very high potential in the use of *Airborne Laser Scanning* (*ALS*) (figure 2.4) for the recognition of archaeological features in the near-surface, while in the archaeological site, it is more common to use a *Terrestrial Laser Scanner* (*TLS*) (figure 2.5). However, both data acquisition platforms generally use the *Light-induced Detection And Ranging* (*LiDAR*) sensor. For the object scale, the *Handheld Laser Scanner* produces very accurate results.

Figure 2.5: *TLS* system example used for recording the *Sint-Baafs* Abbey [42]

There are, of course, more cost-effective approaches that guarantee the necessary accuracy of the archaeological projects. The work of *Hermon et al.* (2012) [43] and *De Reu et al.* (2013) [44] show the successful use of 3D digitizing techniques, based on digital images, for the archaeological record during a site excavation. Both authors emphasize the great advantages of performing the archaeological record using *Structure from Motion* (*SfM*) based methods which work under the same principles as stereo-photogrammetry [45]. The main benefits are not only the gain in the time spent to record the structural data of an excavation but principally the high accuracy and major scientific value of the recorded data. The *SfM* data can also be combined with data from high and intermediate satellite sensors to assess and document threats to spatially extensive archaeological sites [46].

An interesting 3D acquisition alternative to use in an archaeological site or with archaeological objects are structured light equipment. For example, the *Microsoft Kinect* camera is a low-cost, hand-held *RGB-D* sensor that captures a contiguous *RGB-D* stream (colour and depth) and creates a real-time representation of the recorded archaeological elements [47]. The accuracy of the obtained record is satisfactory for archaeological purposes. This method depends very much on the lighting conditions and, therefore, it is more suitable for indoor use (figure 2.6) [48].

Figure 2.6: Structural light 3D acquisition [48]

(a) Georeferencing targets using GPS System (Courtesy of UAUM)

(b) Author using UAV for 3D data acquisition (*Souto Escuro, Boticas*)

Figure 2.7: *SfM*-based 3D acquisition

In an archaeology project, the 3D acquisition methods can be combined to take advantage of each methods strong points [49]. It is also significant to use GPS systems (see figure 2.7a) and total-stations for a more precise georeferencing of the 3D acquisition, therefore enhancing the accuracy of the archaeological record. Moreover, the aerial 3D acquisition using *unmanned aerial vehicles* (*UAV*) for recording more complex archaeological sites is increasingly being used (see figure 2.7b).

The previously mentioned 3D acquisition techniques produce a 3D point cloud that has to be post-processed later to generate a mesh. The density and accuracy of the generated point cloud depend on the acquisition device. Normally, they are much higher while using laser-based equipment. The point cloud is usually stored in 3D model file formats such as *PLY* (*Polygon File Format*) or *OBJ* (*Object File*) [50][51].

2.3.2 Recording the Invisible

The digital data acquisition techniques are not only important for recording the visible archaeological data but also what is not visible. Therefore, geophysical techniques are frequently used in archaeological projects to evaluate aspects regarding a non-visible reality (for example, the subsoil or the interior of architectonical structures) in a non-intrusive way.

Basically, the aim of these techniques is to create a representation of the subsoil using non-destructive methods. Therefore, Archaeological Geophysics is a non-invasive method to describe archaeological evidence by analysing and interpreting the variation of geophysical properties in the space of archaeological interest.

Archaeological geophysics might be combined with aerial imagery to analyse large areas of territory for landscape archaeology purposes. At a smaller scale, the geophysics methods can also be used to explore an archaeological site to help to decide where to carry out the excavation. There are some geophysical methods that can also be used to analyse archaeological objects and structures from heritage buildings.

These different applications are accomplished using diverse survey techniques. The most common in archaeology are:

- *Magnetometry* — this technique uses sensors to record the local variations of the magnetic field of the geologic materials of the Earth to describe the subsoil of the area of interest. This means that for a region with archaeological interest it is possible to detect magnetic anomalies produced by the alteration of a sedimentary structure. However, the usefulness will depend on the contrast between the magnetic properties of the archaeological elements and the environment they are laying. Metallic objects generate big anomalies, therefore magnetometry is not adequate to urban environments. There are basically two types of magnetometers that can be used either for wide areas or for the archaeological site, respectively.

- *Resistivity* — this survey method measures the electrical properties of the soil, by injecting a current into the ground and assessing how it is altered. There are different ways to carry out this method, however, the *earth resistivity tomography* (*ERT*) is very common in archaeology because it enables the generation of a 3D model of earth resistivity. The humidity and mineral compositions of the soil influence the results, since these factors affect the stability of the electrical conductivity.

- *Ground Penetrating Radar (GPR)* — this survey method is based on electromagnetic pulses that are transmitted into the ground by an emitting antenna. The changes in the propagation media generate reflections that are sequentially recorded by the antenna receiver. Each reflection has a concrete arrival time. Since the velocity of the pulses into the propagation media is a known value, it is possible to determine the depth of the objects that generate the recorded reflections. For archaeological purposes, the frequency range of the *GPR* antennae varies between 100MHz and 900MHz. The higher frequency antennae are more adequate to detect small objects, while the lower frequency equipment reaches greater depths.

2.3.3 Summary

The irreplaceable value of cultural heritage demands extremely careful 3D acquisition protocols, regardless of the technology and devices used. In archaeological projects, where an interdisciplinary research team has often to deal with diverse archaeological scales, different protocols might be used. Table 2.1 proposes, for each archaeological scale, the most suitable 3D acquisition methods to record everything (visible or not) that might have archaeological interest.

Regarding the visible data acquisition methods, the *ALS* system is only used at the territorial scale, while the *SfM* methodology associated with a *UAV* has the necessary versatility to be used at any scale of the archaeological record. The 3D data record at an archaeological site can be performed with the widest variety of methods (all, except *ALS*). At an archaeological object level, it is not common to use UAV in the acquisition process of the 3D data, however, depending on the size of the object it might be used. Eventually, the choice of the appropriate method depends on the experience of each team in its use, on the specific conditions of each site, on the required level of detail and also on budget constraints.

	Territory	**Archaeological Site**	**Archaeological Object**
ALS	X		
TLS		X	X
SfM		X	X
SfL		X	X
SfM+UAV	X	X	X
Magnetometry	X	X	
Resistivity	X	X	
GPR		X	X

Table 2.1: 3D acquisition methods used in archaeological projects, according to their different scales

With regard to the acquisition of non-visible 3D data using geophysical methods, all the referred methods are suitable to be used at archaeological sites. Also at the territory scale, both magnetometry and resistivity can be commonly used. However, at the scale of the archaeological object, only the *GPR* methodology can be used, but mainly in large stone objects.

2.4 3D Representation

The early 3D representations of archaeological sites and objects began during the late eighties and early nineties. These representations were promptly accepted for dissemination purposes, but its importance for the archaeological research was not immediately recognized. Currently, it is almost unthinkable to start an archaeological project that does not consider resources for 3D representation.

There are several techniques to perform the 3D representation of archaeological elements.

An extremely useful modelling technique is *Constructive Solid Geometry* (*CSG*) because it can easily build up complex shapes based on more simple primitives, such as cylinders, spheres, cubes, cones, torus, closed spline surface or swept solids. These primitives are conveniently combined using boolean operations such as union, intersection and subtraction (see figure 2.8). This modelling technique is available in some software systems, such as *Blender*, *Maya*, *AutoCAD* or *3DStudio*, and modelling languages like the *Virtual Reality Markup Language* (*VRML*) or *X3D* (*XML* syntax based successor of *VRML*). Therefore, both the software system or the modelling languages are frequently used in archaeological projects.

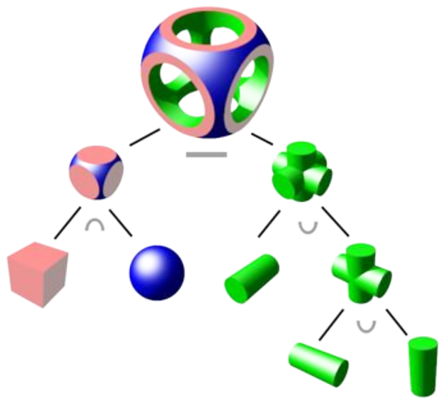


Figure 2.8: Schematic representation of a CSG object

These modelling software systems also support other techniques, such as *Non-Uniform Rational B-Splines* (*NURBS*), which are also valuable for archaeological modelling. *NURBS* modelling is based on splines and enables a very realistic creation of organic forms and curved surfaces (very common in archaeology). It is even more intuitive than *CSG*, though less rigorous. Nevertheless, both techniques fail to record the modelling process, unless all modelling options are properly documented for future memory. An important characteristic of these modelling techniques is their absolute dependence from the archaeological interpretation and relative independence from digital 3D acquisition methods. Actually, this modelling procedure can be based on the simple 2D archaeological record. The visual realism of the 3D model can be enhanced with texturing procedures. The textures are obtained by defining the material properties of the archaeological elements and using photographic information from the archaeological record. To complete the 3D representation, the digital model has to be georeferenced. Throughout the various phases of the traditional modelling workflow (see figure 2.9), the digital model has to be scholarly validated to ensure the accuracy of the final 3D representation.

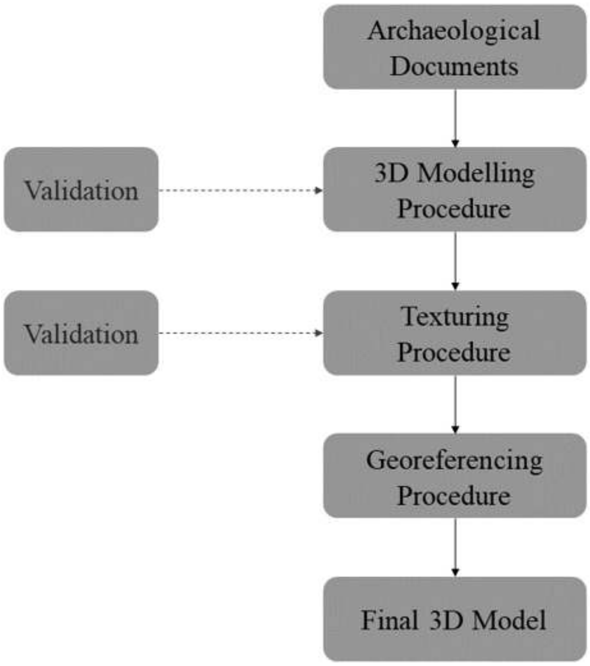


Figure 2.9: Traditional 3D modelling workflow in Archaeology

Another important modelling technique used for archaeological purposes is *procedural modelling*. *Procedural modelling* is a robust method, that uses programming languages for efficiently defining a semantic description of a building to generate a 3D polygonal model. This type of 3D modelling technique has important application in areas like architecture and urban planning. However, in the last decade, it has also been used in the 3D representation of archaeological sites, such as ancient Rome and Pompeii [52]. This modelling approach has great acceptability for representing Greco-Roman buildings and urban environments since classical architecture generally obeys to systematic regularity, based on well-known rules set by Vitruvius [53]. Some tools that might be considered to implement procedural modelling are *Blender*, *3DS Max* or *CityEngine*.

Historic Building Information Modelling (*HBIM*) is an alternative technique that uses attributes and parameters to create a 3D representation of archaeological data, particularly of architectonic nature. *HBIM* comprises the design and construction of a parametric library based on documented architectural rules that range from the Roman epoch to the modern age. The use of these historical data is an added value to ensure the detail of the 3D objects regarding the used construction materials and methods. The final step to enhance the realism of the 3D objects comprises the mapping of the parametric objects onto the point cloud. Like *procedural modelling*, this 3D representation methodology is particularly adequate for architectonic objects. The method is thoroughly described in [54] and a list of possible *HBIM* tools can be considered in[55].

The increasing use of 3D acquisition techniques during the archaeological record is changing the methodologies and procedures used in the 3D representation of archaeological elements [56]. A major difference in the workflow of this 3D representation procedure is the minimal influence of archaeological interpretation during the modelling phase because it relies to a great extent on the obtained point cloud. Therefore, the modelling process does not necessarily depend on traditional 3D modelling software but on 3D meshing algorithms such as *Poisson Surface Reconstruction* methodology or the *Delaunay Triangulation* algorithm. The next step is the texturing procedure, which is based on image information of the object of interest. This 3D representation procedure is completed with the segmentation of the mesh into concrete clusters of archaeological interest, that typically represent objects that range from archaeological structures to stratigraphic units. This last step is supported by archaeological research and continuously validated by experts. This 3D representation procedure can be performed either with commercial or free software systems like *CloudCompare* [57] or *MeshLab* [58]. The fact that most 3D acquisition devices already have their own *GPS* systems allows the 3D representation to be immediately positioned correctly. But even if the *GPS* system is not present, the correct georeferencing of the ground control points that surround the archaeological element makes possible its almost immediate geo-referencing.

2.4.1 Archaeological Sites and Structures

Initially, archaeological 3D representation was thought to be a simple reconstruction procedure, as in Architecture and Urban Planning. However, soon the modelling teams realised the need for more complex research efforts to understand and interpret the source data. This was experienced in [59], mostly because of four limitations found in the provided archaeological field data:

- the archaeological data recording procedure offered inconsistent interpretations and was not favourable for modelling purposes;

- the archaeological drawings rested on the individual skill of the excavator and, therefore, might present inconsistent rigour;
- the charts and drawings did not adequately describe the spatial relationships between forms;
- the data provided an insufficient supply of three-dimensional information.

This research experiences highlighted the need for cautious records and extremely careful and detailed analysis of the excavated data, particularly regarding the analysis of three-dimensional placement and spatial relations of the excavated elements. In fact, 3D models in Archaeology force the resolution of ambiguities and inconsistencies, which in turn induce more accurate interpretations that lead to new discoveries. Also, as it is suggested in [60], the reconstruction process of archaeological or historical sites induces the construction of knowledge models.

The work presented in [61] discussed innovative methods for creating 3D models of historic sites. For the 3D data acquisition, the authors use a time-of-flight scanner. All the scans will be aligned using overlapping pairs, and afterwards, an *iterative closest point* (*ICP*) algorithm will be used to create a final registration. This data can be used to create meshes of the scanned object, which can be texture mapped and used for photorealistic viewing. Some identified problems include automatic data acquisition, view planning to select the best viewpoints and real-time model creation and visualization. Still, in spite of the problems, the authors were convinced of the application of this research area in digital archaeology and the immense amount of projects that today use these methods applied to the 3D representation archaeological structures confirm that they were right.

Another approach regarding the modelling of archaeological sites is presented in [62]. The authors have created an annotated 3D model of Pompeii, based on archaeological data, using procedural modelling. These annotations include semantic data, such as building age, land usage and window/door labels. *Heagler et al.*(2009) present in [52] an alternative way to model large sites and to represent uncertainty. More recently, *Danielová et al.*(2016) also presented an extremely interesting work that is concerned with the reliable 3D reconstruction of ancient structures and to a coherent representation of ambiguities and uncertainties. While the structures are presented in different levels of detail using procedural modelling, the uncertainties are quantified and visualized based on a fuzzy logic approach [63]. The previous examples represent Roman sites and Mayan structures, therefore the use of procedural modelling for 3D representation purposes is particularly adequate taking into account the regular nature of this type of architecture.

Considering the ease in which archaeological data can be acquired using *SfM* methods and the reliability of these data, there is a significant quantity of 3D representation regarding archaeological structures of different typologies that are based on this methodology. *López* et al. (2016) [64] present an innovative method that uses the *SfM* data to produce volumetric models and processes these models using *BIM* to obtain useful information, such as plans, sections and orthophotographs, for research and publication purpose. In [65] the authors show the potential of *SfM* methods also in the representation and visual analysis of rock art. The main benefits are not only the cost-effectiveness but also the metric accuracy and graphic quality of the 3D representation.

2.4.2 Archaeological Artefacts

Besides the reconstruction of archaeological sites, there has been considerable work towards the reconstruction of artefacts. *Kampel* et al. (2003) present a reconstruction method for pottery based on its profile sections [66]. The reconstructed objects can later be used for pottery analysis and classification purposes. A more refined approach is presented in [67], where the method is tested in a large range of archaeologically relevant pottery types. Here the results were so promising that the authors suggested this method as a practical and reliable tool in archaeological research. The same authors present in [68] a morphological analysis of ceramic assemblages, using an objective, automatic and computerized method for clustering and classification of ceramics.

The photorealism of ceramic artefacts is very important for virtual exhibitions. The research work presented in [69] suggests a new method that can be used to separate the diffuse and specular reflection components in a multi-view image sequence. First, the image sequence is normalized by the estimated illumination colour. The second step replaces the specular chromaticity by the corresponding diffuse chromaticity. This method is tested for modelling *Yixing* ceramic teapots. The shape is obtained by a laser scanner and the diffuse image sequence is used to generate the texture map. This method is not applicable to grey-scale images.

The 3D representation techniques of archaeological artefacts are also important to create tangible reproductions. In the past, the cost of digital fabrication techniques was significantly high-priced. However, nowadays the value of 3D printing devices reduced considerably due to the usage of cost-effective techniques, such as *fused deposition modelling* (*FDM*), that still ensures high precision of the produced objects [70]. This type of archaeological artefacts reproduction has application in areas that range from education in museums, support for visually impaired people or even production of tailored packaging for safely transport cultural objects [71].

2.4.3 Stratigraphic Units

Almost all archaeological excavations use the concept of excavation units, also known as stratigraphic units since most archaeological sites are composed of several superimposed layers (strata) of archaeological deposits. A stratigraphic unit, which is the basic element of the recording procedure, is a 3D volumetric component of archaeological remains within a site under excavation. Although using this concept for years, archaeologists heavily rely on 2D representations of the stratigraphic units for analysis and interpretation purposes, as well as for publication.

Losier et al. (2007) presents a procedure to generate 3D models from *GPS* positions taken at the top and bottom of the excavation units boundaries [72]. It discusses two geometrical modelling approaches (voxel and tetrahedron) that are used by *GoCAD* 3D modelling tool. Once the geometric models are produced, it is possible to manipulate them and perform various kinds of queries. The geometrical model can also be published as *VRML*. The main objectives of this work are (1) to improve data analysis techniques and (2) to help archaeologists to plan more efficiently their excavation strategy.

More recently, *Valente* et al. (2017) present a 3D representation method for stratigraphic units based on *SfM* techniques to ensure accuracy and exchangeability [73]. The resulting 3D reconstructions are used at a posterior phase to perform spatial analysis on *GIS* and dissemination of the excavation results on the web.

2.4.4 Summary

There is a considerable diversity of 3D representation techniques that are commonly used to virtually illustrate archaeological elements at different scales. The most common techniques in archaeology and the situations in which they are used are recorded in table 2.2.

3D Meshing is widely used in the virtual representation of archaeological elements of different scales, mostly because of the cost-effective and user-friendly image-based data acquisition methods. *Procedural Modelling* and *HBIM* are mainly used for representing architectural information with archaeological interest, while *CSG* and *NURBS* techniques are also used to virtually represent archaeological artefacts. The stratigraphic units are better represented using 3D meshing techniques because they assure a greater accurateness, while an archaeological site might be virtually reconstructed using all the major available 3D reconstruction techniques, depending on the final purpose of the virtual model.

	Archaeological Site	**Archaeological Object**	**Stratigraphic Units**
CSG	x	x	
NURBS	x	x	
Procedural Modelling	x		
HBIM	x		
3D Meshing	x	x	x

Table 2.2: 3D representation Methods used in different scales of the archaeological research

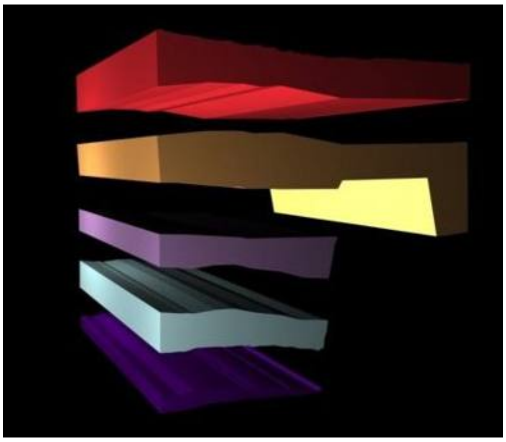
2.5 Computer Application Projects in Archaeology

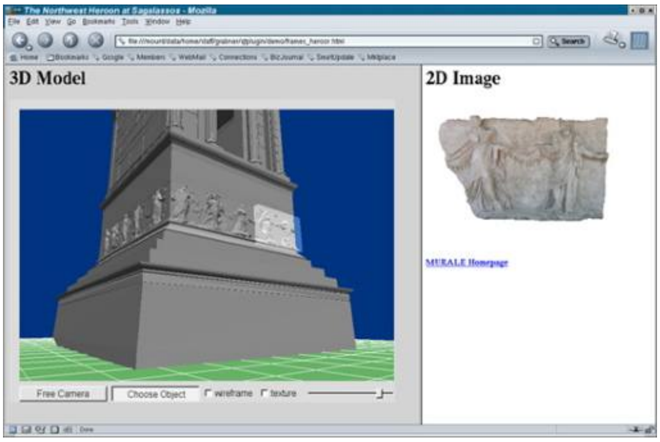
Over the last three decades, there has been an exponential growth of computer application projects in archaeology. Initially, the objectives of the projects were focussed on the three-dimensional restitution of archaeological data for analysis and interpretation and for the dissemination of results. More recently, there has been a refinement of the objectives of these projects, which also began to focus on the 3D record of an archaeological site and on teleimmersion.

2.5.1 3D MURALE

The *3D Measurement and Virtual Reconstruction of Ancient Lost Worlds of Europe* project (*3D MURALE*) was funded by the European Union and had the purpose to develop 3D measurement, reconstruction, database and visualization tools [74, 75]. These tools were tested in *Sagalassos*, a major Roman site in Turkey. According to *Green et al.* (2001, 2002), the recording tools were developed for the measurement of terrain, stratigraphy, buildings, building blocks, pottery, pottery sherds and statues on the archaeological site. Afterwards, these measurements are stored in the multimedia database of *3D MURALE*. The reconstruction process comprises two distinct procedures that reconstruct pottery and buildings, respectively.

(a) Integration of text, images, and recorded objects for Museum visualization purposes





(b) Exploded view of stratigraphy

(c) Internet visualization

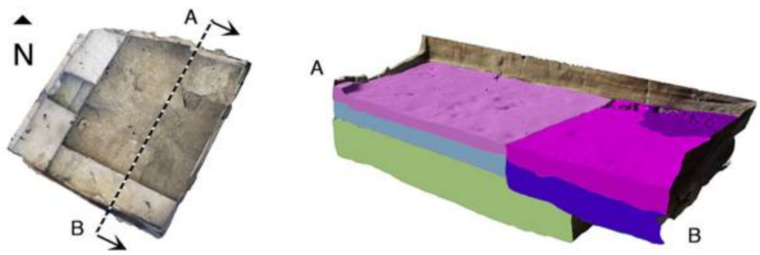
Figure 2.10: 3D MURALE system

The visualization tool takes into account that Archaeology deals with large and complex scenes, different users and time-dependent data. Therefore, the data visualization using the *3D MURALE* system can be accomplished with three different tools:

- The first tool, called *STRAT* (figure 2.10b), is able to perform real-time stratigraphic visual simulations for archaeological analysis and hypothesis testing.
- The second tool is more concerned with the visualization of the reconstructed site (figure 2.10a), which can be used by researchers to test and document their hypotheses or by a larger audience to understand how everything would look like.
- The last tool, implemented as a web browser plugin, is a client/server rendering system, called *WebCAME* (figure 2.10c), that provides view-dependent access to huge 3D data sets [76].

2.5.2 3D Archaeology at Catalhoyuk

(a) Catalhoyuk south area



(b) *SfM* 3D layers

(c) Immersive interaction

Figure 2.11: 3D Archaeology at Catalhoyuk [77]

The *3D Archaeology at Catalhoyuk* project started in 2010 and its primary goal is to record, document and visualize, using virtual environments, all the phases of an archaeological excavation using new digital approaches [78][79]. The 3D documentation workflow is based on *SfM* techniques, *TLS*, 3D *GIS*, *UAV* capabilities for 3D mapping and *GPR*. To perform the archaeological data analysis, interpretation and curation the team developed a multi-platform, scalable virtual reality tool [77]. Therefore it is possible to virtually reproduce not only the current state of the archaeological site (see figure 2.11a) but the entire archaeological excavation process and make the excavation virtually reversible.

The 3D reconstruction of deposits enable an interpretation phase with two separate approaches, which are not contextualized in one research workflow:

- The first approach involves the interpretation and documentation during the excavation (figure 2.11b);
- The second approach is related to the reconstruction process after the excavation.

This project also uses teleimmersive technology to enable researchers to work simultaneously in the same immersive cyberspace (figure 2.11c) to potentially generate new interpretations and simulation scenarios [80].

2.5.3 Summary

The use of digital technologies in all phases of the archaeological process is increasingly present in archaeology projects. The table 2.3 shows that, although the two projects have been developed approximately a decade apart, both use digital technologies at all phases of the archaeological process. There are, however, two aspects that draw our attention: on the one hand, in the most recent project, interaction with data also incorporates concepts of cooperative work and immersive environments; on the other hand, with regard to dissemination there is also, in the most recent project, an increased concern for open access to 3D data.

The *Catalhoyuk* project also shows a strong tendency to dematerialize the entire archaeological process. In fact, in this project, for some years now, the registry tends to be exclusively digital and three-dimensional, which favours all aspects related to 3D representation and archaeological visualization.

The focus of this work is precisely the visualization and 3D representation of archaeological data throughout all phases of the archaeological process. Particular attention will be placed on defining strategies that incorporate the traditionally available solutions in the context of the archaeological project.

	3D MURALE	**Virtual Catalhoyuk**
3D Acquisition	X	X
3D Representation	X	X
3D Interaction with data	X	X
Cooperative Environment		X
Immersive Environment		X
General Analysis	X	X
Statigraphic Analysis	X	X
Interpretation	X	X
Dissemination	X	X
Open Access to 3D data		X

Table 2.3: Use of digital technologies in distinct and time-separated archaeology projects

Chapter 3

Visualization in Archaeology

The visualization of data has been a human concern for centuries. In fact, the most primitive known and documented visualization techniques were charts that represented the position of stars and other celestial bodies and maps for navigation. The concept of coordinates was already present in the Ancient Egyptian civilization where it was used for urban landscapes organization and planning and later on map projections of a spherical earth converted into latitude and longitude were used by Ptolemy in the 2nd century [81].

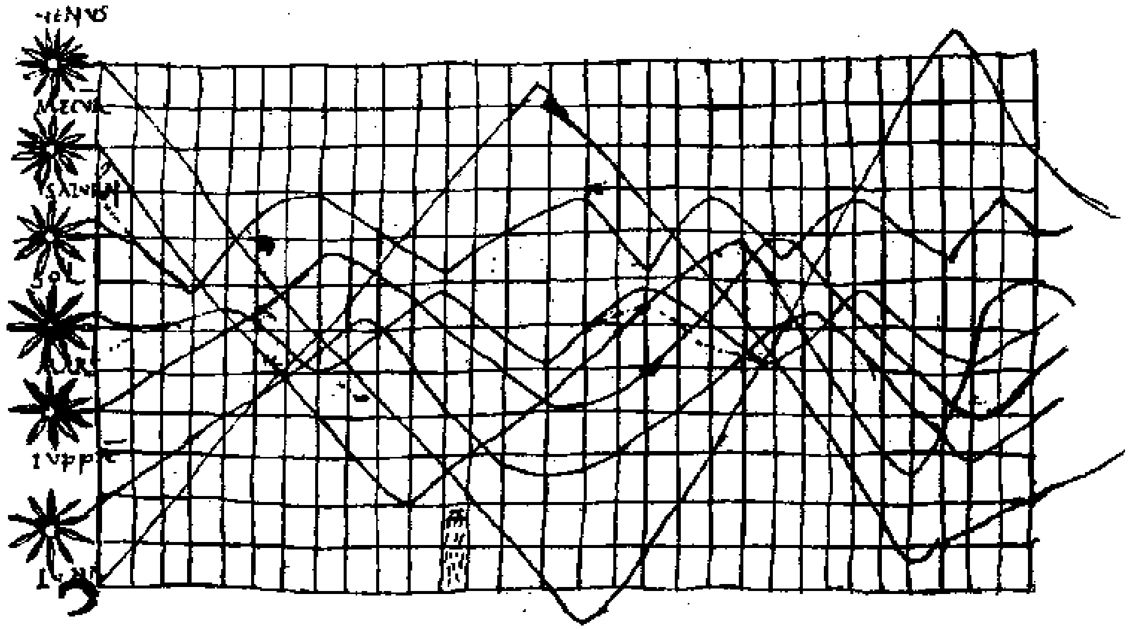


Figure 3.1: Illustration of planetary movements, from the 10th century – anonymous author [82]

A remarkable example of quantitative information visualization is an anonymous publication from the 10^{th} century representing the orbital movements, over space and time, of the seven most prominent celestial bodies (see figure 3.1) [82]. This graph denotes the idea of a coordinate system and the use of something very similar to the graph paper.

By the 16^{th} century, it was already possible to map geographic and celestial locations accurately due to the development of important triangulation methods. Until the present day, several of the visualization techniques that have emerged were applied both in a scientific context and in day-to-day situations. Because of the influence of computer science research, visualization has evolved enormously (the first *GIS* and interactive systems for 2D and 3D statistical graphics appeared during the seventies) and turned into a solid and multidisciplinary research area with a wide range of visualization methods available for every desktop computer. A thorough description of the evolution and history of visualization is available in [83] and in [81].

3.1 A Brief definition of Visualization

It is possible to find several definitions of visualization that have emerged and evolved over the years in a complementary approach. According to [84], visualization is mostly about the computer-assisted transformation of data (or information) into a visual representation that might be interactively explored to gain understanding and insight into the data. More recently, *Azzam et al.* [81] have consolidated this characterisation by referring that data visualization is a process that relies on three criteria:

- Qualitative or quantitative data;
- Representative image of the raw data;
- Readable image, able to support exploration, examination and communication of the data.

The first criterion is easily accomplished because during the evaluation of a question it is frequent to gather different forms of data that can potentially be visualized. Understandably, each type of data involves unique approaches and visualization methods to highlight the knowledge that they contain. To guarantee the second criterion it is important to ensure that the significant information is not omitted, that certain data is not overrepresented and that the visualization accurately reflects the information of the data. This conditions will prevent misunderstandings during the visualization process. If the last criterion is effectively achieved, then it is highly probable that knowledge will be extracted from the initial data through the visualization process. However, for successful visualization, the obtained knowledge should be used to increase the understanding of a subject, which in turn will facilitate the analyses and dissemination of the data.

There are numerous areas where visualization methods can be applied to. These areas range from Medicine, Physics, Chemistry, to Social Sciences, like History or Archaeology. This means that visualization methods can be applied to areas with, predominantly, spatio-temporal attributes and to areas with relational and tabular data. Therefore, visualization techniques can be largely categorised into data visualization (more general than scientific visualization) and information visualization, respectively. Thus, data visualization is concerned with the visual representation of quantitative and categorical data, while information visualization is generally applied to the visual representation of large-scale collections of non-numeric information, such as files and lines of code in software systems (software visualization) [85], library and bibliographic databases, networks of relations on the internet [84].

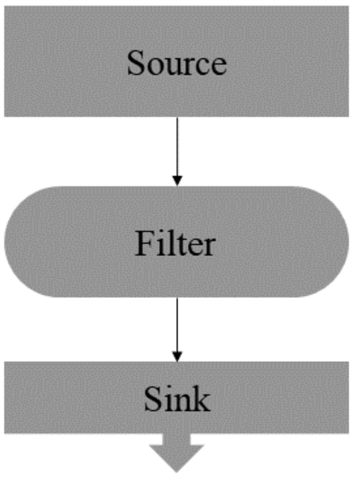
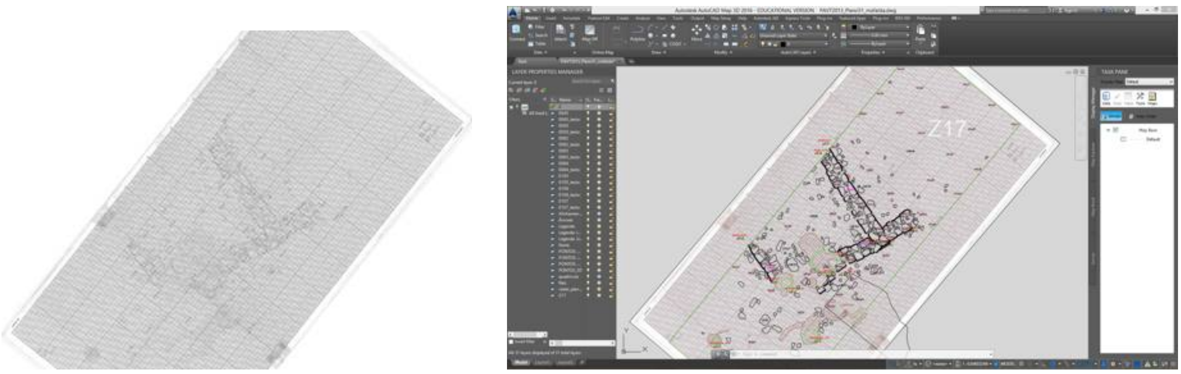


Figure 3.2: Most simple visualization workflow

Both data and information visualization can be successfully accomplished using existing, commercial or open-source visualization systems. Each of these systems will, most probably, have distinct approaches to describe the path from the data acquisition to the image generation, usually referred to as visualization pipeline. However, this data flow (figure 3.2) has normally a modular structure with three different types of modules: *sources*, *filters* and *sinks*. The *source* module is normally a file reader or a data generator, while the *sink* module is normally a file writer or a rendering module. The *filter* module, generally, transforms data from (at least) one input to one (at least) output. The idea behind the modularity is to encapsulate algorithms in an interchangeable way, where the output from one or more modules can be connected to the input of one or several modules [86].

3.2 Influence of Visualization in Archaeology

The visualization of archaeological data was always present in Archaeology. From the very beginning, archaeological drawings and sketches were used to support the interpretation of the Past. Traditionally, the drawings may range from the creation of general maps, to the detailing of architectural and sculptural elements, or to the definition of plans and sections of the considered elements (see figure 3.3a) and are usually later vectorised (see figure 3.3b) to ensure reliable digital support of the archaeological record. These drawings support the archaeological research, while a more thorough archaeological illustration and even detailed scale models are used for dissemination purposes.



(a) Manual field drawing (Courtesy of UAUM)

(b) Field drawing vectorization using CAD tool (Courtesy of UAUM)

Figure 3.3: Field drawing of an archaeological element, recorded during the excavation

Currently, these visualization techniques are still used in Archaeology, but they are now mostly applied using computer-based tools, such as *GIS* software, *Computer Assisted Design*

(CAD) software or raster graphics software. At the *Archaeological Unit of the University of Minho*, all excavations are recorded with images which are used to create a 3D surface and rigorous representation of the archaeological site.

3.2.1 Visualization Strategies

It would be an extremely time-consuming task to elaborate a comprehensive list of all the techniques and technologies (2D and 3D) that have been used in the last years and it would prove to be impractical due to the amount of the combinations and diversity in approaches that have been employed. To overcome such limitations, *Foni et al.* (2010) present a very exhaustive research work about visualization strategies applied to Cultural Heritage items [87], while *Llobera* (2011) performs an exceptional review and evaluation of the advantages of using modern visualization techniques in Archaeology, particularly in archaeological discovery and discourse [9].

The main paradigms of *Foni et al.* are mostly concerned with the visualization of archaeological data and they propose a general classification and analytical comparison based on inherent characteristics and criteria that can be identified at varying intensity across all projects in this area. There are four main hubs in use for classification:

- the amount of virtuality;
- the degree of interactivity;
- the visual consistency and precision;
- the degree of automatism.

The authors of this study consider that the strategies to be taken into account when visualizing Heritage items are:

- *Restitution drawings* — it is a standard procedure and an essential step for an excavation team and extremely important to be experienced by students;
- *Augmented Pictures* — visual integration and direct confrontation of selected restitution hypotheses with the present reality;

- *Scale models* — physical reproduction of a scale model typically exhibits a relatively mild visual consistency and precision. Normally, the closer the scale to 1:1, the more detail can be included in the model (see figure 3.4);

- *Physical reconstructions* — on-site physical reconstitutions offer the visitor of an archaeological site the possibility to visually experience a representation of the past. However, the historical accuracy and global precision of such a strategy is sometimes questionable;

- *Interactive scale models* — this visualization strategy is comparable to the approaches that use static scale models. However, the moving parts of the scale model are used to visually illustrate their role, purpose or construction method (see figure 3.5);

- *Live experiments* — a particular case of the interactive scale models used in Experimental Archaeology, where the replicas are made at a scale 1:1;

- *Computer Graphics rendering* — it depends on the appropriate choice of modelling techniques, on the preparation of the illumination models, on the accuracy of the textures and material properties, and on the reliability of the hypothesis that underlies the chosen virtual restitution attempt, to achieve a visually consistent and historically precise virtual 3D reconstruction (see figure 3.6);

- *Digital catalogues* — this visualization strategy is usually used for dissemination purposes in museums, specifically to be published in electronic formats;

- *Digital Panoramas* — this visualization strategy has been repeatedly employed and extensively used because, in spite of the short an inexpensive development cycle, it still offers comparable degrees in both visual consistency and precision as digital catalogues while allowing at the same time increased interactivity;

- *Real-time virtual reality simulations* — The visualization attempts depend on the same assumptions of computer-generated renderings. However, while static rendering takes several minutes to produce one image, real-time visualization has to generate a minimum of twenty-five rendered images per second. Nevertheless, these simulations have a remarkable level of interactivity, allowing the user to freely manipulate the visualized objects and directly explore and modify the virtual worlds;

- *Stereoscopic visualizations* — the great advantage of this visualization strategy is the capacity of stimulating the viewer's perception of depth. Also, comparing with the plain real-time simulations, the visualized items have a slightly superior level of virtuality and perceived visual consistency;

- *Real-time Augmented Reality simulations* — these simulations generally exhibit simplified geometrical models to achieve real-time capabilities, therefore decreasing the degree of visual consistency and precision. However, this strategy can offer interesting possibilities and useful application because of their interaction capabilities and capacity to visually stimulate the viewer;

- *Digitally augmented movies* — this kind of movie is generally a process that involves several people over long periods of time and requires a great amount of time and effort to reach completion. Usually, they have visual consistency but denote lack of scientific accuracy;

- *Semantically supplemented 2D and 3D representations* — this visualization strategy enhances the visual representation of an item adding graphical data, such as 2D photographic images, digital panoramas or 3D virtual models, to the visualised content. In some cases, it can be a valuable asset and a powerful tool for analysing documentation related to the visualised content.

Figure 3.4: Scale models[1] of some hillforts from the *Terva Valley Archaeological Park* (Boticas, Portugal) (Courtesy of UAUM)

[1]These scale models are available for the public at the *Centro Interpretativo de Bobadela* (Boticas, Portugal)

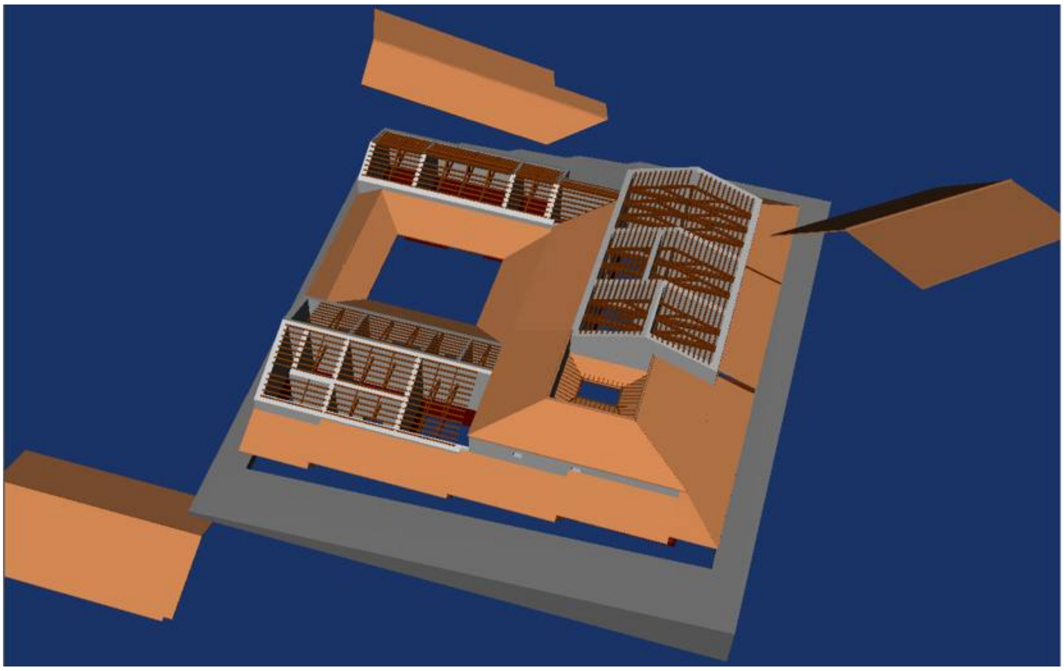


Figure 3.5: Interactive scale model of the *domus* of *Carvalheiras* (Braga, Portugal)

Figure 3.6: Computer Graphics render of the *triclinium* from the Roman *Villa* of Milreu (Faro, Portugal) (Courtesy of UAUM)[2]

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[2]This image was produced for the RTP documentary entitled *Escrito na Pedra*, authored and directed by the journalist Maria Júlia Fernandes

Summary

It is important to have in mind that data acquisition techniques used during the recording process of a cultural item influence the techniques used for visualization purposes. These data acquisition strategies are used to enhance the automatism, to improve precision and visual consistency and to increase interactivity.

Naturally, each visualization strategy has distinct characteristics and criteria that determine its greater or lesser use in the different phases of the archaeological process. The table 3.1 shows the predominant characteristics associated with each visualization strategy, its applicability in the different phases of the archaeological process, as well as the associated advantages and weaknesses. The major characteristics of the visual strategies are visual consistency, while the phase that most benefits from the visualisation strategies are the dissemination phase.

Strategies	**Characteristics**	**Applicability**	**Pros**	**Cons**
Restitution drawings	Visual Consistency	Record	Essential for excavation Student training	Time-consuming 2D
Augmented Pictures	Visual Consistency Virtuality	Interpretation Dissemination	Visual Integration Hypotheses evaluation	Time-consuming 2D
Scale Models	Visual Consistency	Dissemination	Consistent Precise	Time-consuming Static
Physical reconstructions	Visual Consistency Interactivity	Dissemination	Experience a representation of the past	Questionable historical accuracy and precision
Interactive Scale models	Visual Consistency Interactivity	Analysis Interpretation Dissemination	Illustration of role purpose and construction method	Time-consuming
Live Experiments	Interactivity	Dissemination	1:1 scale	Time-consuming Spatial constrain
CG Rendering	Visual Consistency Virtuality Automatism	Analysis Interpretation Dissemination	Consistent Precise	Depends on the reliability of the restitution hypothesis

Digital catalogues	Visual Consistency Interactivity	Dissemination	Consistent Precise	2D
Digital panoramas	Visual Consistency Interactivity	Dissemination	Consistent Precise Short and inexpensive development cycle	2D
Real-time VR simulations	Visual Consistency Interactivity Virtuality Automatism	Analysis Interpretation Dissemination	Consistent Precise	Depends on the reliability of the restitution hypothesis
Stereoscopic Visualizations	Visual Consistency Virtuality	Analysis Interpretation Dissemination	Consistent Perception of depth	2D
Real-time AR simulations	Visual Consistency Interactivity Virtuality Automatism	Analysis Interpretation Dissemination	Interaction capabilities Visually stimulate the viewer	Simplified geometrical models to achieve real-time capabilities
Digital augmented movies	Visual Consistency Virtuality	Dissemination	Consistent Precise	Time-consuming Rarely scientifically precise
Semantically supplemented 2D and 3D representations	Visual Consistency Interactivity Virtuality Automatism	Analysis Interpretation Dissemination	Enhanced visual representation	Time-consuming

Table 3.1: Visualization in Archaeology

3.2.2 Computer-assisted Archaeological visualization

As mentioned in [9], Archaeology relies to a great extent on (1) recognizing and comparing patterns, (2) spotting outliers, (3) identifying relationships and (4) building arguments in order to provide for thorough data interpretation. Therefore, regardless of archaeological procedures applied in the course of archaeological research, it is implied that the archaeologists will have to deal with visualization issues. Traditionally, archaeological visualization is mostly based on drawings of the archaeological finds, sketches of the stratigraphy, site plans and profile drawings or distribution maps. Even though advanced computational tools are increasingly used in Archaeology, the production of visual communication forms remain extremely condensed. Visual communication is essentially used to enhance the interpretation of data made by archaeologists and for the production of graphical objects that improve the graphical quality of the traditional visualization support. In these terms, the use of visual communication is lacking in its potential to improve the understanding and insight of the archaeological data.

The visualization of archaeological data using computer-supported tools is not a recent issue. In fact, there has been great concern regarding this subject and several virtual representation and visualization methods have been suggested by several authors. A classic reference regarding computer-assisted archaeological visualization is the *Winchester Graphics System*, which provided a fully 3D visualization environment for archaeological data [88]. The features of this graphics system enabled new explorative possibilities in Archaeology.

Still, most of the research in archaeological visualization has been aiming towards the development of computer applications, used for the interpretation and dissemination of archaeological data, focusing on the realistic or photo-realistic representation of the data [89]. But there is as well great visualization concern regarding the earlier stages of an archaeological excavation [90][91][92]. Other visualization methods have also been proposed for uncertainty representation and for illustrating archaeological elements.

Realistic or Photo-realistic Visualization of Archaeological Data

CAD and *GIS*-based systems are the main visualization tools widespread amongst archaeologists. In fact, since the 1980's, archaeologists are using these systems' 3D capabilities for spatial data visualization [27]. As refered by *González-Tennant* (2015), the past use of *GIS* in archaeology might be categorized in various ways [93]. In fact, the author recognizes the difficulty to categorize how *GIS* was used in archaeology but suggests three distinct classes. The first category is *Inventory and Geospatial Database Management* since *GIS* is an extremely effective tool for performing the inventory of an archaeological site and to relate the field data (i.e. *GPS* data, photography and plan drawings) with datasets from other sites. Another category is *Geospatial Analysis* which is extremely important because it enables archaeologists to analyse the data in order to enhance the understanding of the territory, either for site management or research purposes. Particularly important are the *Cost Surface Analysis* that might assess the travel costs or determine the most likely routes between archaeological places. Also significant is the *Visibility Analysis* for modelling experimental elements and to improve the perception of past landscapes. The third category is the *Mapmaking and Data Visualization* which is essential to generate maps locating archaeological features and to discover patterns.

These categories that define the way *GIS* is used in archaeology will continue to be enormously significant, both for site management and research. However, present *GIS* technology might also be combined with immersive environments to enhance the archaeological exploration of 3D landscape data, with clear advantages both for research and dissemination [94]. Immersive environments for archaeological visualization, but not integrated with *GIS*, were already used by the beginning of the 21^{st} century to enhance the analysis methods employed at an archaeological site [95][96]. Nevertheless, a recent and interesting understanding of new paths for the future of *GIS* in archaeology can be found in [97] and in [98].

An exceptional example of archaeological intra-site research is presented in *Katsianis et al.* (2008) [90] and *Tsipidis et al.* (2011) [92]. The proposed method is based on a 3D digital workflow that enables the recording of archaeological observations in a *GIS* environment that supports tools for exploring the archaeological information. They suggest the use of *GIS*-based technology to record and analyse archaeological data. The principal objective is the realistic visualization, using a commercial *GIS* package, of archaeological excavation data through 3D representations that help archaeologists to have a consistent image of the excavation process and their interpretive results. In this way, the developed system facilitates the data management of the excavation context and provides constructive insights during the interpretation process. The prehistoric site of *Paliambela Kolindros*, in Greece, was used as a case study to validate this kind of visualization approaches.

A remarkable *GIS*-based digital archaeological workflow is also proposed by *Petrovic et al.* (2011) [99]. The authors have developed a system that integrates *GIS*-based artefact and material sample datasets of *Khirbat En-Nahas*, Jordan, with *LiDAR*-based excavation data from the same site. Thus, the archaeologists have full access to a virtual archaeological site with all the captured record available for examination. Among other features, this system is able to perform an interactive visual analysis using a dynamic sectioning and measurement tool.

Figure 3.7: Archaeological information in an unique 3D visualization environment [92]

More recently, the *Swedish Pompeii* project illustrates the advantages of integrating the improved archaeological record, based on advanced 3D acquisition systems, into a *GIS* environment. *GIS* is an extremely important technology to manage and analyse archaeological information and to visualize the interconnection between different types of data. Therefore, the objective of this work was to establish an efficient and robust workflow to implement geo-referenced 3D textured models to be effectively explored in archaeological research [100].

The *REVEAL* project, which is based on Computer Vision, Pattern Recognition and Machine Learning research, is an excellent system for archiving, extract information from and visualize archaeological site-excavation data. The system automatically registers different data types, like tables, site plans, sketches, images, videos and 3D laser scans and displays 2D and 3D data. This application is able to estimate a 3D surface, curves and other geometries from multi-views and accurate inexpensive 3D estimation from single-view structured light. It is also possible to use *REVEAL* for automatic or semi-automatic estimation of ceramic pots and glass objects from dense-data laser scans and from their broken fragments. This software is available, as an open-source project, to the Archaeology community and it is open to inputs from its users. This software has been used to study the *Crusader Citadel at Apollonia-Arsuf*, in Israel [91].

The urban evolution project of Braga is an essential work that uses technologies based on Computer Vision, 3D Computer Graphics and *GIS* to reconstruct and visualize the evolution of the city, from the Roman foundation to our days. The project development is based on a multidisciplinary approach, where the combined results of archaeological activity and studies, integrated into dynamic information management are valued. This approach allowed the creation of new record, analysis and dissemination of information platforms (see figure 3.8), where metadata, drawings, graphic registration and 3D models are fundamental for research regarding urban archaeology and the dissemination of their results [101].

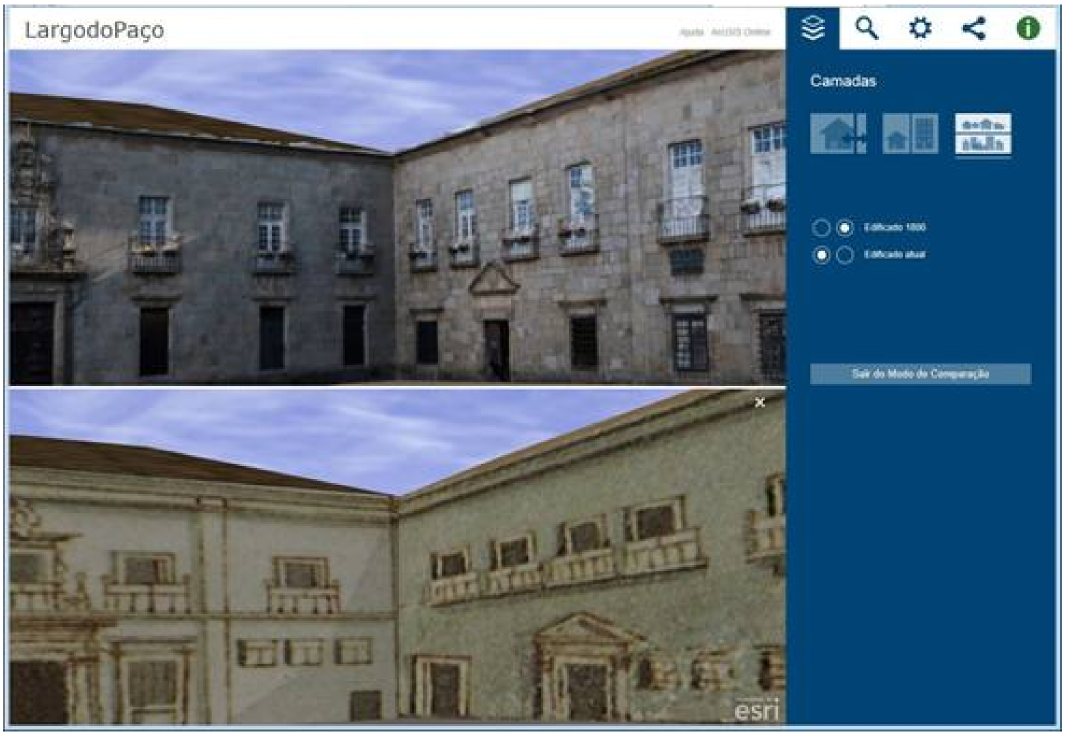

Figure 3.8: 3D model comparison with *CityEngine*'s webviewer (Courtesy of UAUM)

Visualization of Archaeological Uncertainty

The visualization of uncertainty is an essential question for visualizing archaeological structures or artefacts. The work of *Strothotte et al.* (1999) suggests some non-photorealistic rendering techniques to visualize uncertainty in ancient Architecture, to resolve the difficult task of representing imprecise or incomplete information that frequently occurs in archaeological sites [102]. Also, *Roussou et al.* (2003) argue that non-photorealistic rendering is useful for virtual heritage representation, particularly for virtual archaeology [103]. Therefore, they consider equally important to develop computer graphic techniques to enhance photorealism and to develop artistic means of expression that can give a view of the site but without photographic realism.

Zuk et al. (2005) suggest a very interesting methodology to deal with temporal uncertainty in [104]. Their research focuses on an application designed to integrate and visualize the temporal uncertainty for multiple 3D archaeological datasets with different dating. The authors introduce a temporal time window for dealing with uncertainty and review several visual cues that are adequate for revealing uncertainty within the time window. It is clear that this method and application is an easy way to cognitively merge multiple data that represent different time periods. This kind of visualization will serve both the general public and the domain experts. For the general public, it is able to provide comprehensible visual explanations, while for the domain experts it might be useful in cognitive tasks such as hypothesis building.

The concern about the certainty of an archaeological model is also an important research issue, as shown in the work of *Houde et al.* (2015). The authors merged information from standing architecture, excavated remains, surveyed plans and *GPR* data to explore the representation of uncertainty in archaeological research [105]. Their methodology involves the definition of seven levels of certainty and the creation of three distinct 3D models of the site based on colour, transparency and texture, respectively. After building the different models, the authors created a survey for users to evaluate separately the three models regarding its simplicity in interpretation, its clarity in the representation of uncertainty, the difference in uncertainty among features and its usefulness in research. According to their results, the preference is for colour and transparency models to represent the different levels of uncertainty.

Archaeological Illustration

The archaeological illustration is not a visualization issue *per se* but rather a methodology to visually represent archaeological elements. However, it is an important methodology to represent the archaeological elements in a simple but sound way and, therefore, an essential but time-consuming step within the archaeological process. Consequently, computer-based archaeological illustration has been also a concern in the archaeological community.

Luo et al. (2011a, 2011b) present both in [106] and [107] an innovative method for 3D line drawing applied to archaeological illustration. This method can generate line drawings with multiple scales and different view directions. According to the authors, this method is more accurate than the traditional manual method and avoids expensive and time-consuming 2D drawings. Another very interesting work regarding the shape illustration of archaeological artefacts is due to *Harary et al.* (2010). In [108], the authors suggest the use of 3D Euler Spirals to complete the shape illustration of Hellenistic oil lamp-curves.

Another noteworthy approach to archaeological sketching is presented in *Chen et al.* (2010) [109]. The authors introduce a tool, based on a 3D sketching system for architectural design, that organizes images and drawings of archaeological sites. The sketching system allows the user to represent structures and it is extended by allowing the users to include images and drawings of archaeological sites into space (see figure 3.9).

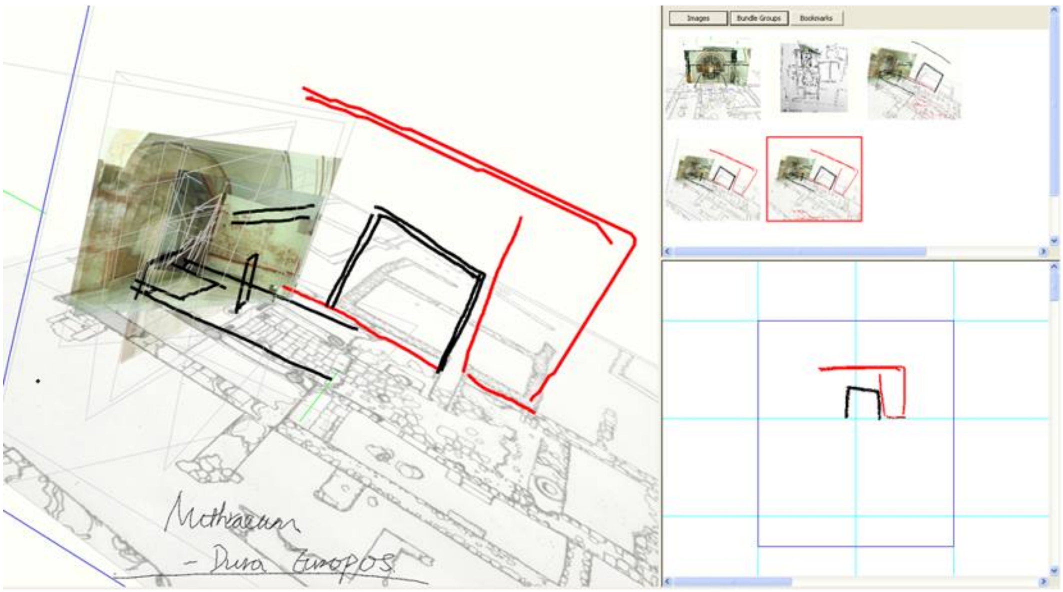

Figure 3.9: Sketching environment for archaeological sites [109]

Nevertheless, the traditional archaeological illustration is still very present in the archaeological publication. However to avoid inconsistencies, to overcome the different skill levels of the illustrators and to increase the objectivity of the archaeological representation, alternatives such as laser scanning and image-based modelling are increasingly considered [110][111]. These 3D representations can further be used to produce reliable replicas by means of 3D printing.

3.2.3 Summary

Computer-assisted visualization in archaeology seeks to contribute positively to the analysis and successful understanding of archaeological elements, regardless of their different scales. The various projects presented before, clearly show that there is a great preference for visualization strategies that support 3D archaeological data in all distinct archaeological visualization typologies. The table 3.2 associates to each visualization typology the aims that should be fulfilled, the acquisition and representation methodologies and the most adequate visualization strategies.

	Aims	**Methodologies**	**Strategies**
	Inventory	*CAD* and *GIS*	Interactive scale models
	Analysis	Computer vision	Computer graphics rendering
Realistic/Photo-realistic Visualization	Management	Computer graphics	Virtual reality simulations
	Gain insight	Pattern recognition	Augmented reality simulations
		Machine learning	Semantically supplemented representations
		Laser scanning	
	Analysis	Computer graphics	Computer graphics rendering
Visualization of Uncertainty	Gain insight	Material properties	Virtual reality simulations
		CAD	Augmented reality simulations
			Semantically supplemented representations
	Analysis	*CAD*	Restitution drawings
Archaeological Illustration	Gain insight	Computer vision	Augmented pictures
		Computer graphics	Semantically supplemented representations
		Laser scanning	Computer graphics rendering

Table 3.2: Aims, methodologies and strategies associated to distinct visualization typologies

This work will focus on realistic and uncertainty visualization. Therefore, 3D acquisition and representation will be based on *CAD*, Computer Vision, Computer Graphics and Pattern Recognition methodologies. In addition, the visualization strategies considered are fundamentally the Interactive Scale Models, the Computer Graphics Rendering and the Semantically Supplemented 2D and 3D Representations.

Chapter 4

Evaluation of Visualization procedures during the Archaeological Process

Visualization methods support the communication of implicit knowledge and encourage new thinking [112]. Therefore, visualization methods are commonly used during the successive stages of the archaeological process. However, it is difficult to determine which visualization methods are more intensively used in each stage and, also, which stage of the archaeological process is more demanding regarding visualization needs. Aiming at understanding which stages of the archaeological process most regularly use visualization methods, a Web-based survey directed at archaeologists was carried out. A further aim was to realize the influence of both traditional and computer-based visualization methods during the different stages of the archaeological process.

4.1 Design of the user survey

An efficient methodology to evaluate how visualization methods are being used by archaeologists during the various stages of the archaeological process, as well as to represent different archaeological entities, is to conduct a user survey. The survey was designed to be as inclusive as possible and encompassed archaeologists from different countries, of different ages and professional experiences, working in different chronological periods and associated to institutions that have different purposes (Universities, Public Institutions and Private Companies). The implementation of the user survey was divided into three distinct stages: (1) the preparation, validation and sending of the questionnaire; (2) the answering process; (3) the validation, analysis and interpretation of the received responses with the purpose of drawing some conclusions. The first and third stages are author-dependent and follow the steps that can be seen in the workflow presented in figure 4.1. The second stage depends on the availability and willingness of those who received the questionnaire.

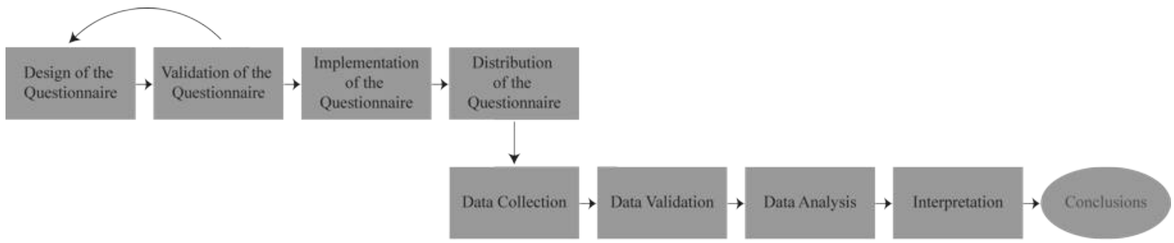

Figure 4.1: User survey workflow

In order to ensure clearness and conciseness, the user survey was structured in four distinct sections:

- *Personal data* — this section was responsible to collect the information about the respondents. To ensure their anonymity, the questions were mainly related to age, field experience, employer and experience in a given historical or prehistorical period of time. The evaluation of the personal data of the respondents was a precious indicator of their heterogeneity.

- *Computer-assisted tools in Archaeology* — here the aim was to identify the computer-assisted tools, both software and hardware-based, used in the distinct stages of the archaeological process, in particular during the archaeological record (in the field), the analysis and interpretation of the archaeological data (in the Lab) and the publication/dissemination of the archaeological data.

- *Computer-based modelling tools in Archaeology* — in this section the purpose was, on the one hand, to evaluate the importance of modelling tools in archaeology and, on the other hand, to highlight the most common tools used both for 2D drawing and 3D modelling.

- *Computer-based visualization tools in Archaeology* — this section aimed at evaluating the importance and use of traditional and computer-based visualization tools in Archaeology. Furthermore, it expected to identify what kind of visualization methods (realistic and non-realistic) are mostly used during the different phases of the archaeological process and to visually represent archaeological entities.

Also, an attempt to determine which kinds of visualization techniques are mainly used for visualizing archaeological data was made. As mentioned in chapter 3, Archaeology often deals with a certain degree of uncertainty, therefore it is truly significant to understand if realistic and non-realistic visualization methods are used and what kind of visualization techniques the archaeologists prefer. The questions focus on the purpose of computer-based visualization tools and the context in which they are mostly used.

To the best of the author's knowledge, no similar work has been carried out regarding the use of visualization and modelling methods during the archaeological process and for the representation of archaeological entities. Therefore, the design of the survey was a careful and progressive task, since the questions and the types of answers had to be the most appropriate and extremely clear.

Since the survey was intended to assess the use of visualization and modelling methods, most of the answers are chosen from a five-point ordered frequency scale. The values of the scale comprise *never*, *rarely*, *sometimes*, *often* and *always*. Thus, the respondents are asked to rate the frequency in which they use certain methods or techniques, both during the different phases of the archaeological process, or to visually represent different archaeological entities. Some other answers are selected from a five-point ordered quantity-rate scale to assess the importance of some visualization or modelling methods/techniques. This quantity scale comprises the values, *not at all*, *poor*, *some*, *plenty* and *extremely*.

4.2 Validation and distribution of the survey

The validation of the user survey was carried out by four archaeologists from the *Archaeological Unit of the University of Minho*. The chosen archaeologists have a wide experience in the coordination of archaeological excavations and two of them are faculty members of the *History Department* of the *University of Minho*.

The assignment of these archaeologists was to read the questionnaire carefully and check whether the questions were worded in an appropriate manner and were intelligible. They also gave valuable suggestions regarding the order in which the sections and questions should be formulated and the type of response that should be available. Particularly important were the suggestions about the questionnaires extension. All such suggestions were considered for redesigning some parts of the questionnaire.

The implementation of the questionnaire was carried out with the *Google Docs form editor* and later distributed, by e-mail, to a set of archaeologist known to the candidate. Also, for the participants to be as representative as possible, the link was sent to two different archaeologists groups (*Quaternary Prehistory Mação Google Group* and *LinkedIn Group CAA: Computer Applications and Quantitative Methods in Archaeology*). The purpose was to get a sufficient number of answers that could provide meaningful results. Appendix A presents the complete layout of the survey sent to archaeologists.

4.3 Data collection, validation and analysis

Over three months, 39 responses were received from archaeologists working in Portugal, Spain, UK, Germany, Italy and Greece. However, most of the responses came from Portuguese archaeologists. All responses were immediately stored in *Google Docs*, for later processing.

Except for two responses, all were accepted for this survey. The two rejected responses were not complete and did not answer any questions regarding modelling or visualization methods.

The age of the respondents varies between 23 and 51 years old and the median age of the sample is 31. Thus, it is possible to create two subgroups: the junior archaeologists (younger than 31 years) and the senior archaeologists (older than 31 years). There are 18 junior and 19 senior archaeologists, therefore these two subgroups are relatively balanced.

Regarding the professional experience, the respondents have between 1 and 30 years of experience and the median of professional experience is 8 years. Similarly to age, it is possible to establish two subgroups: the less experienced (less than 8 years experience) and the more experienced (more than 8 years experience). However, these two subgroups are fairly uneven since 15 participants are less experienced and 22 are more experienced. On the other hand, the behaviour of these two subgroups will most likely be very similar to the behaviour of the younger and older archaeologists. Thus, the subdivision into these two subgroups was not considered.

The number of responses is relatively balanced from archaeologists that work in Universities (12), Public/Governmental Institutions (13) and Private Companies (9). Also, the respondents had more experience in the *Iron Age*, *Roman Period* and *Middle Ages* and less experience in *Palaeolithic*, *Mesolithic* and *Neolithic Periods* (figure 4.2).

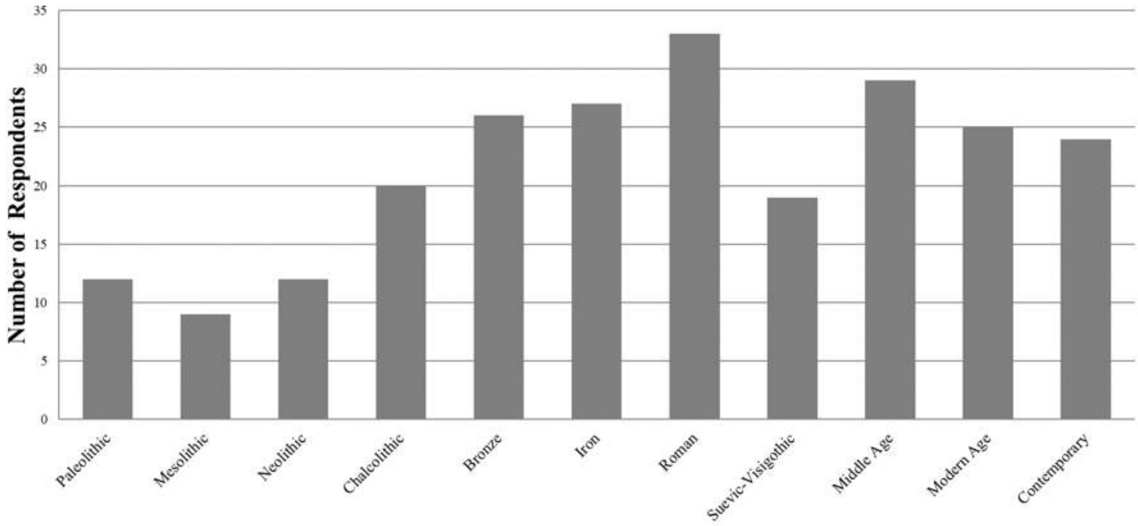

Figure 4.2: Chronological period experience of the respondents

The valid responses were analysed with *Microsoft Office Excel*, using *Excel*'s statistical, logical and mathematical functions [113].

4.4 Results

To understand how visualization tools and methods are used in Archaeology, the four sets of questions from the last section of the user survey were thoroughly analysed.

The first set of questions is related with the use of traditional visualization tools in Archaeology. The aims are to understand (1) if archaeologists consider traditional visualization tools important, (2) if they effectively use them and (3) which of the traditional visualization tools do archaeologists effectively use. The next set of questions concerns the realistic visualization methods. In this case the aims are to understand (1) if archaeologists are familiar with them, (2) in which phase of the archaeological process are they mostly used and

(3) what archaeological entities are mostly represented using these methods. The third set of questions has the same objectives as the previous one, but for non-realistic visualization methods. The last set is only concerned with which visualization techniques are used for visualizing/representing archaeological data.

When evaluating whether or not archaeologists use particular visualization tools or methods, the responses are grouped as:

- *N/R* – if there is no answer;
- *Yes* — if the answer ranges between *rarely* and *always*;
- *No* — if the answer is *never*.

4.4.1 Traditional visualization

The traditional visualization tools considered are:

- *Scale Model*;
- *Maps/Cartography*;
- *Archaeological Drawings*;
- *Archaeological Illustration*.

The validated answers show that 71% of the respondents consider very or extremely important to use traditional visualization tools. They also show that 72% of the inquired archaeologists actively use traditional visualization tools. It is also particularly interesting to notice that no one considered traditional visualization tools not to be important and that no one answered that they never use traditional visualization tools.

Regarding the considered tools, the answers reveal that an expressive percentage of the inquired archaeologists use illustration, maps and drawings (91,89%, 89,19% and 86,49%, respectively), whereas only 67,57% use scale models (see figure 4.3). Interestingly, none of the respondents have answered that they never use drawing and illustration, but a small percentage (2,7%) do not use maps. There is also a small percentage (5,41%) that use other traditional visualization tools, such as photography.

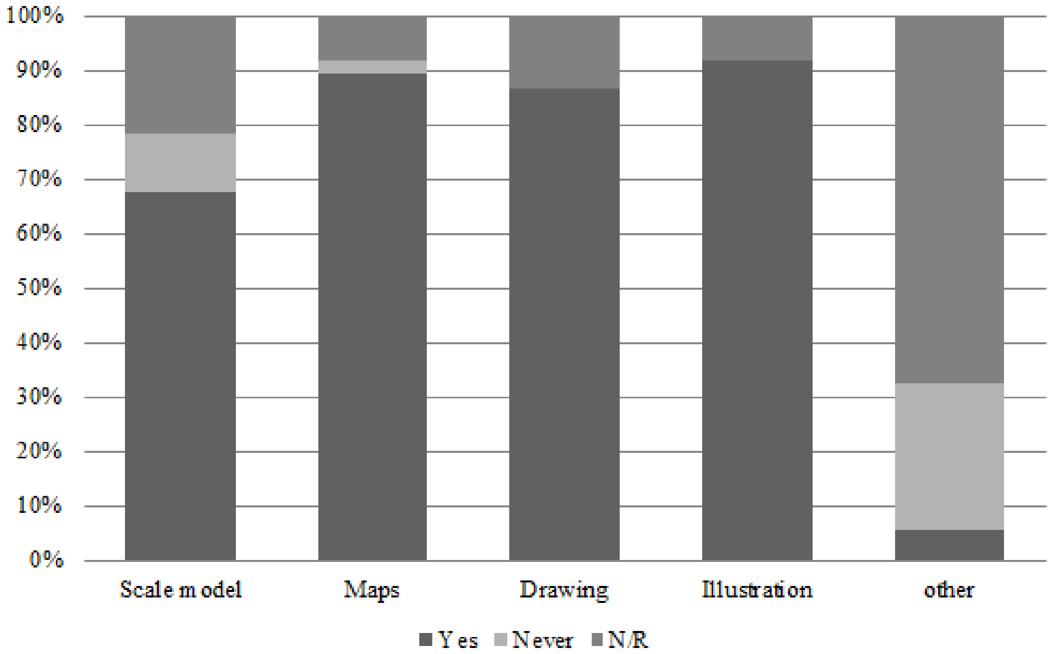

Figure 4.3: Traditional visualization tools use

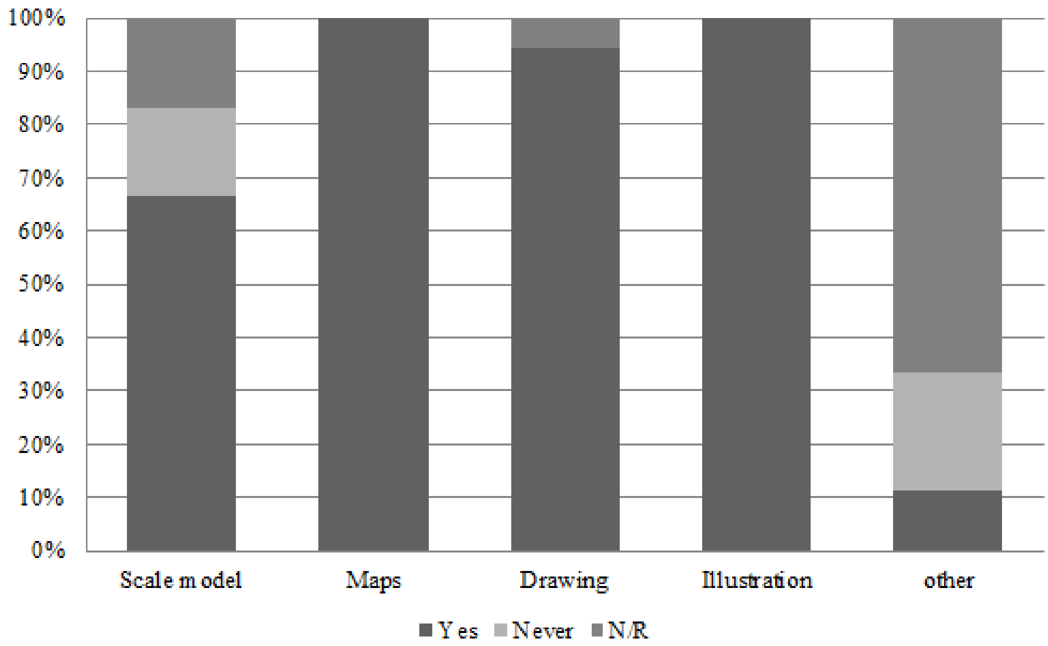

Figure 4.4: Traditional visualization tools use among junior archaeologists

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However, the behaviour among junior and senior archaeologists is not homogeneous. According to the survey all the junior archaeologists use maps and illustration and a very expressive percentage (94,44%) use drawing. Only 66,67% have ever used scale models, while about 11,11% use other visualization tools besides the ones considered (figure 4.4). Among senior archaeologists the behaviour is different. The traditional visualization tool most used is illustration (84,21%) and the less-used are scale models (68,42%). The survey indicates that both maps and drawings are used in a similar percentage (78,95%) by the senior archaeologists (figure 4.5).

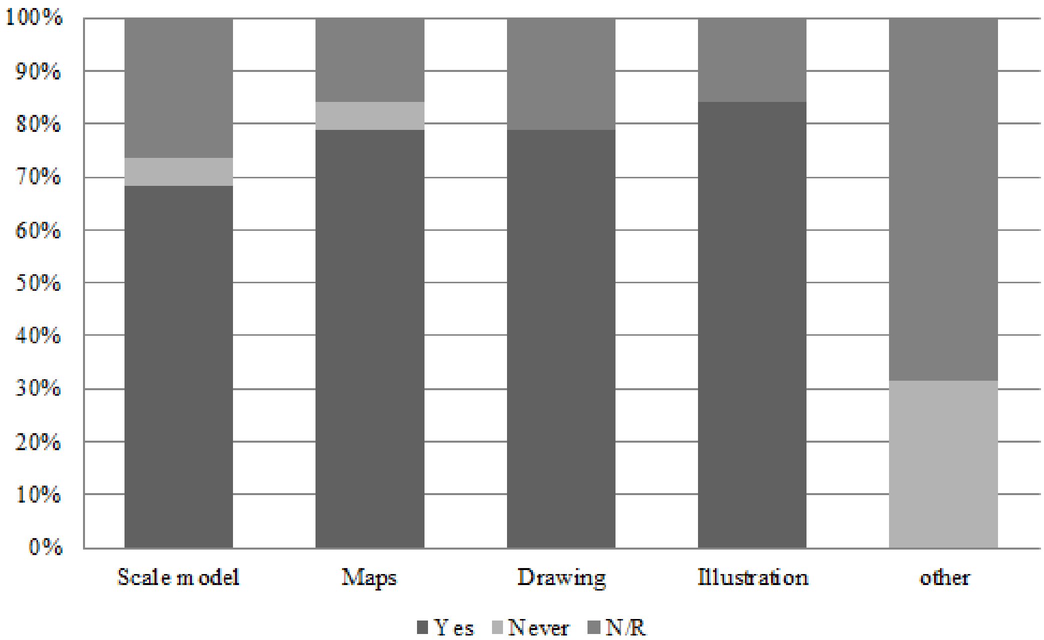


Figure 4.5: Traditional visualization tools use among senior archaeologists

4.4.2 Computer-based visualization tools

Approximately 84% of the inquired archaeologists have the opinion that it is very or extremely important to use computer-based visualization tools (figure 4.6). In fact, 54% think it is extremely important to use computer-based visualization tools. Actually, since no response regarding the importance of using computer-based visualization tools was rated as *poor*, it can be generally assumed that archaeologist are aware of the importance of computer-based visualization tools. However, regarding the effective use of computer-based visualization tools in archaeology, 3% of the inquired archaeologists answered that they rarely use computer-based visualization tools, but about 84% of the respondents use them regularly (figure 4.7).

In the context of computer-based visualization tools, two questions were presented to the participants, regarding their familiarity with realistic and non-realistic visualization methods, respectively. About 29% of the responses indicate that the respondents have *poor* or *no* familiarity with realistic visualization methods, while 21% indicate *poor* or *no* familiarity with non-realistic visualization methods.

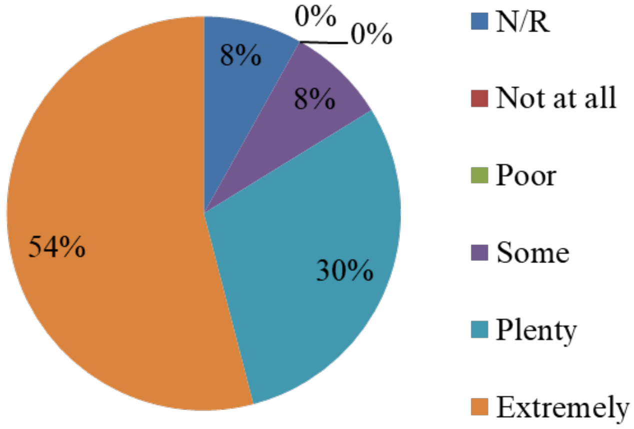


Figure 4.6: Importance of using computer-based visualization tools

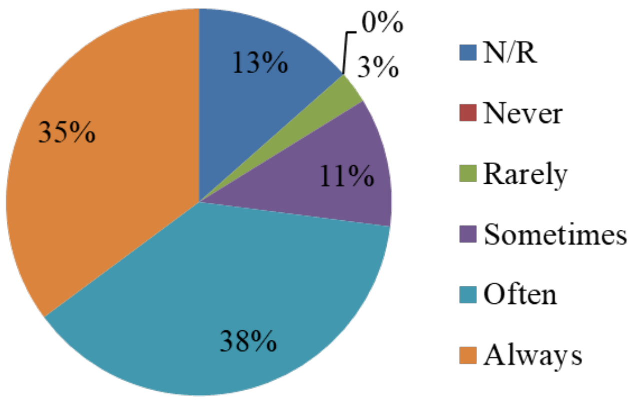


Figure 4.7: Effective use of computer-based visualization tools

Realistic visualization

The realistic visualization methods originate data representations based on accurate geometry or physical properties. It is important to understand if realistic visualization methods are used during the different stages of the archaeological process and what kind of archaeological entities (artefacts, structures or stratigraphic units) are visualized. Thus, it will be possible to infer which existing visualization methods should be improved and which kind of new computer-based visualization tools should be designed and implemented.

The received responses show that realistic visualization methods are used by the majority of archaeologists throughout the different stages of the archaeological process (see figure 4.8). Generically, 62,16% of the participants use realistic visualization in the post-processing of the archaeological record and during the analysis and interpretation stages. This percentage is clearly inferior during the research phase (54,05%) and during the dissemination phase (59,46%). There is a considerable percentage of archaeologists (between 13,51% and 21,62%) that never use realistic visualization methods during the archaeological process and an even greater percentage (between 21,62% and 27,03%) of respondents that did not answer this question.

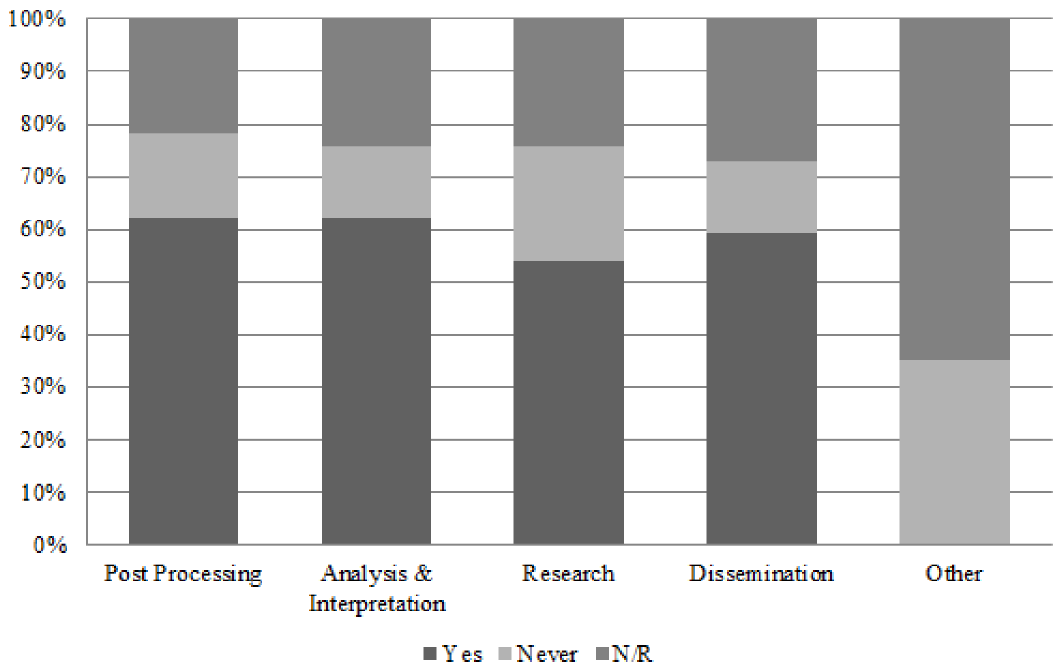


Figure 4.8: Realistic visualization methods during the archaeological process

The junior archaeologists use realistic visualization methods more intensively (66,67%), also during the post-processing of the archaeological record stage, and during the later analysis and interpretation. During the research stage the use of such visualization methods is much inferior (55,56%) and during the dissemination stage the use is about 61,11%. The senior archaeologists use these methods in a very balanced way in all four phases, even though the use is slightly inferior during the research stages (52,63%) and equal (57,89%) in the three remaining stages.

The number of responses was not sufficiently high so that three statistically significant subgroups, regarding the type of employer (Universities, Public Institutions and Private Companies), could be defined. However, the received responses indicate a tendency that archaeologists working for universities use realistic visualization methods mostly during the dissemination stage and less during the post-processing of the archaeological record. Archaeologists working for public institutions mostly use these visualization methods during the post-processing and the analysis and interpretation stage. For respondents working at private companies, the realistic visualization methods are also used during the research and dissemination stages and mostly used during the post-processing.

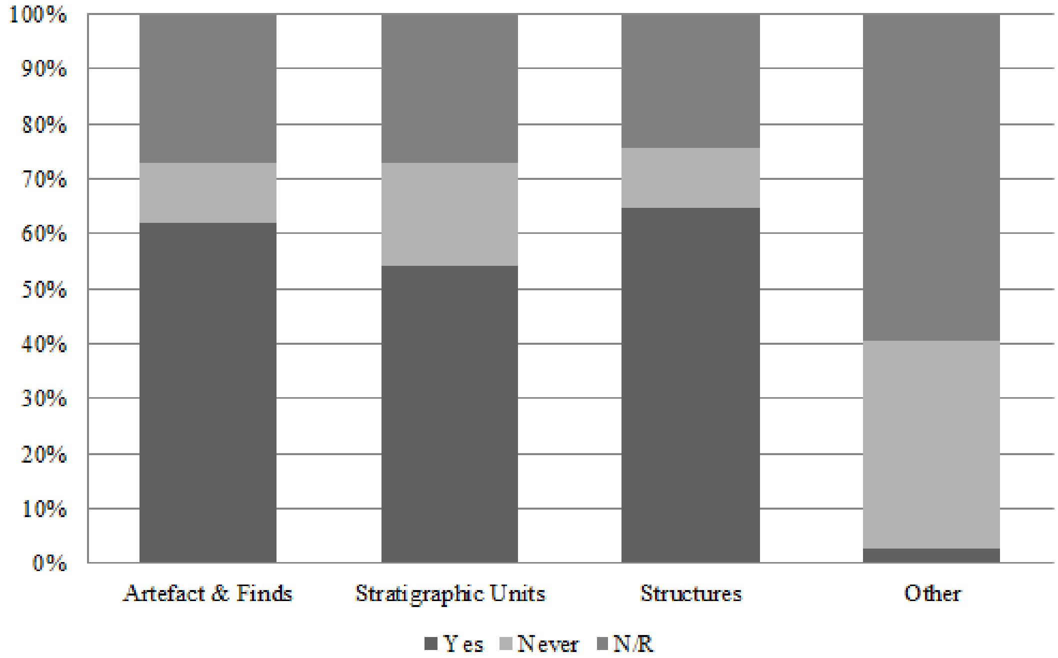


Figure 4.9: Realistic visualization methods for archaeological objects

Analysing now the different archaeological entities considered, approximately 54,05% of the respondents use realistic visualization methods to represent stratigraphic units. This value increases to 64,86% and to 62,16% for structures and artefacts and finds, respectively (see figure 4.9). The percentage of respondents that never use realistic visualization methods to represent archaeological objects varies between 10,81% and 18,92%. However, there is an extremely high rate of archaeologists (24,32% – 27,03%) that did not answer this question.

Junior archaeologists use realistic visualization mostly (61,11%) in the representation of structures and artefacts and finds. This percentage decreases (55,56%) while representing stratigraphic units. The percentage of junior archaeologists that never use realistic visualization methods in archaeological objects varies between 11,11% and 16,67% and the percentage that do not answer is 27,78%.

Considering the senior archaeologists, these realistic visualization methods are mostly used to represent structures and less-used to represent stratigraphic units. The percentage of senior respondents that do not use these methods changes between 10,53% and 21,05% and the percentage of participants that did not answer to this question varies between 21,05% and 26,32%.

According to the responses, the participants that work in universities have a tendency to use realistic visualization methods mostly to represent artefacts and finds and structures. The stratigraphic units are less frequently represented using these methods. The respondents working for public institutions have somewhat different behaviour, since they use these visualization methods to equally represent all archaeological objects. The archaeologists associated to private companies have also a different behaviour they are mostly concerned with representing structures using the realistic visualization methods, and less worried with the representation of the stratigraphic units.

Non-realistic visualization

As with realistic visualization methods it is important to understand how non-realistic methods are used in the successive stages of the archaeological process and what kind of archaeological objects are mostly represented with these methods.

During the archaeological process, non-realistic visualization methods are mostly used during the analysis and interpretation stage (56,76%) and less-used for dissemination (45,95%) (see figure 4.10). About 51,35% of the inquired archaeologists use these methods during the post-processing of the archaeological record and 48,65% during the research phase. There is a high percentage of participants (between 18,82% and 27,03%) that never use non-realistic visualization methods during the archaeological process. Between 24,32% and 27,03% of the participants did not answer the question regarding the use of non-realistic visualization methods during the archaeological process.

According to the received answers, among junior archaeologists the use of non-realistic visualization methods during the stages of the archaeological process varies between 55,56% (analysis and interpretation) and 38,89% (dissemination). During the post-processing of the archaeological record the use of these methods among junior archaeologists is about 50% and decreases to 44,44% in the research phase. There is a considerable amount of younger participants (22,22% – 33,33%) that never use non-realistic visualization methods during the archaeological process and a significant percentage (22,22% – 27,78%) that did not answer this question. The behaviour of older participants is slightly different. Non-realistic visualization methods are also mostly used (57,89%) during analysis and interpretation, but in all the other stages the use is about 52,63%. The number of senior archaeologists that never use non-realistic methods varies between 15,79% and 21,05%, and the percentage of those not answering this question is 26,32%.

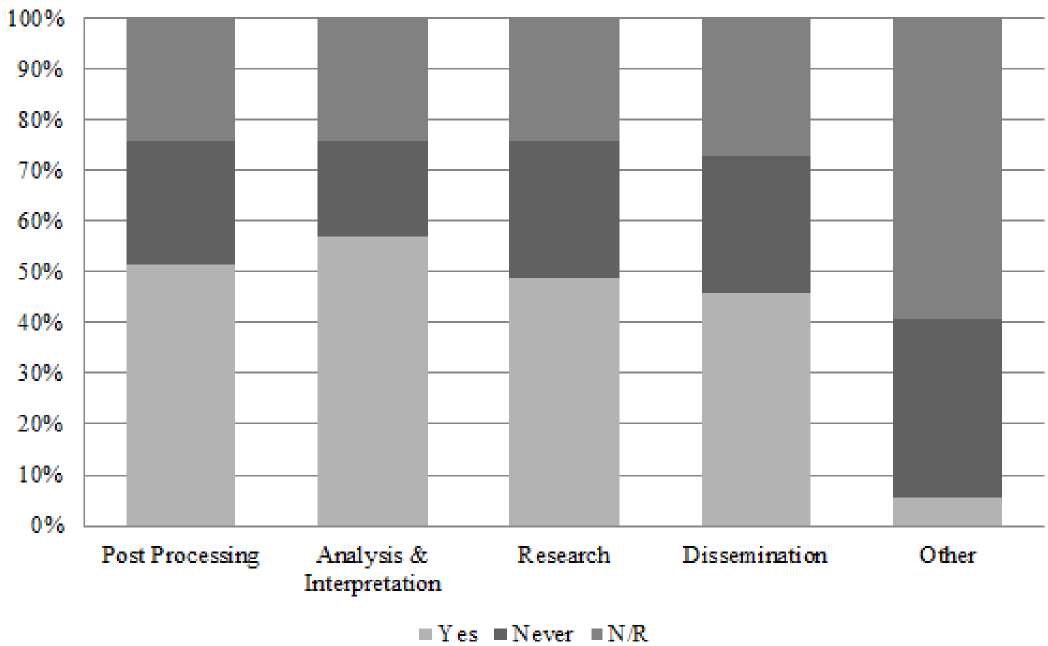


Figure 4.10: Non-realistic visualization methods during the archaeological process

The participants that work for universities and private companies have a tendency to use non-realistic visualization methods mostly during the analysis and interpretation stage, while the archaeologists that work for public institutions mostly use these methods both in post-processing and during the analysis and interpretation stage.

Considering now non-realistic visualization methods to represent different archaeological entities, it is possible to verify, according to the received answers (see figure 4.11), that the participants mostly use these methods to represent structures (54,05%). They are less-used to represent artefacts and finds (45,95%), whereas 51,35% use it to represent stratigraphic units. The percentage of participants that never use these visualization methods varies between 21,62% and 29,73%. The percentage of non-responding participants is 24,32%.

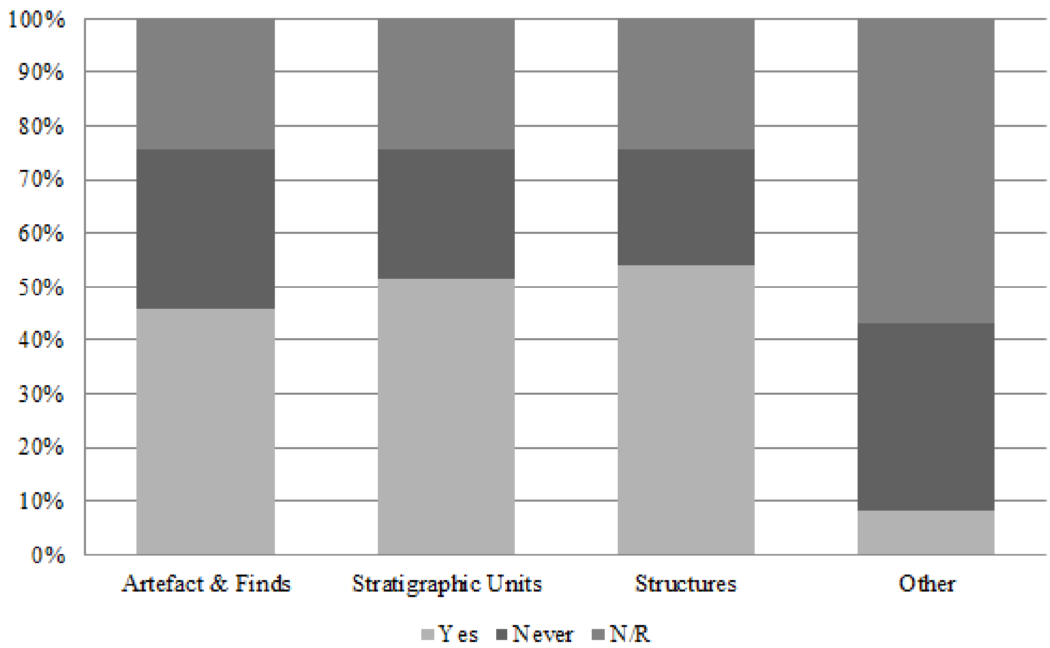


Figure 4.11: Non-Realistic visualization methods for archaeological objects

Among junior archaeologists, non-realistic visualization methods are less-used to represent artefacts and finds (44,44%). But 55,56% use these methods to represent stratigraphic units and structures. There is a considerable percentage of participants that never use these visualization methods (22,22% – 33,33%) and about 22,22% of the junior archaeologists did not answer this question. The senior archaeologists use non-realistic visualization methods more frequently to represent structures (52,63%), while the representation of stratigraphic units and artefacts and finds decreases to 47,37%. Between 21,05% and 26,32% never use non-realistic methods, and 26,32% did not answer this question.

Regarding the received responses, the frequency with which archaeologists who work in universities use non-realistic visualization methods to represent the considered archaeological objects is equal. The same happens with archaeologists that work for public institutions.

However, the behaviour of archaeologists working in private companies is different. In this case, the participants show a tendency to use non-realistic visualization methods to represent structures.

4.4.3 Visualization techniques

This subsection analyses the use of visualization techniques in Archaeology. For this survey, the considered techniques are:

- *tables*;
- *charts*;
- *graphs*;
- *maps*;
- *colour mapping*;
- *glyphing*;
- *cutting/slicing*;
- *2D drawing*;
- *3D modelling.*

Figure 4.12 shows that the most popular visualization techniques are graphs and maps (86,49%). But 2D drawing is also extremely used (83,78%). Colour mapping and cutting/slicing is often used (75,68% and 70,27%, respectively). Tables, glyphing and 3D modelling are moderately used (64,86% and 62,18%, both glyphing and 3D modelling).The less-used visualization technique is charts (51,35%). The percentage of respondents that never use visualization techniques varies between 0% and 18,92% and the percentage of participants that did not answer this question varies between 13,51% and 29,73%.

Among younger participants the most used visualization techniques are graphs, maps and 2D drawing (100%, 94,44% and 88,89%, respectively). Visualization techniques such as colour mapping, cutting/slicing and table are also very frequently used (83,33%, 77,78% and 72,22%, respectively). The less-used visualization techniques are 3D modelling and charts

(55,56% and 50%, respectively). The percentage of younger archaeologists that never use visualization techniques varies between 0% and 27,78%, and between 0% and 22,22% did not answer this question. For older participants, the most used visualization techniques are maps and 2D drawings (both with 78,95%) and graphs (73,68%). Colour mapping, glyphing and 3D modelling is also frequently used (all with 68,42%), as well as cutting/slicing (63,16%). The less-used techniques are tables and charts (57,89% and 52,63%, respectively). Among the older participants there is a moderate percentage (between 0% and 15,79%) that never uses visualization techniques and a considerable percentage that did not answer this question (21,05% – 36,84%).

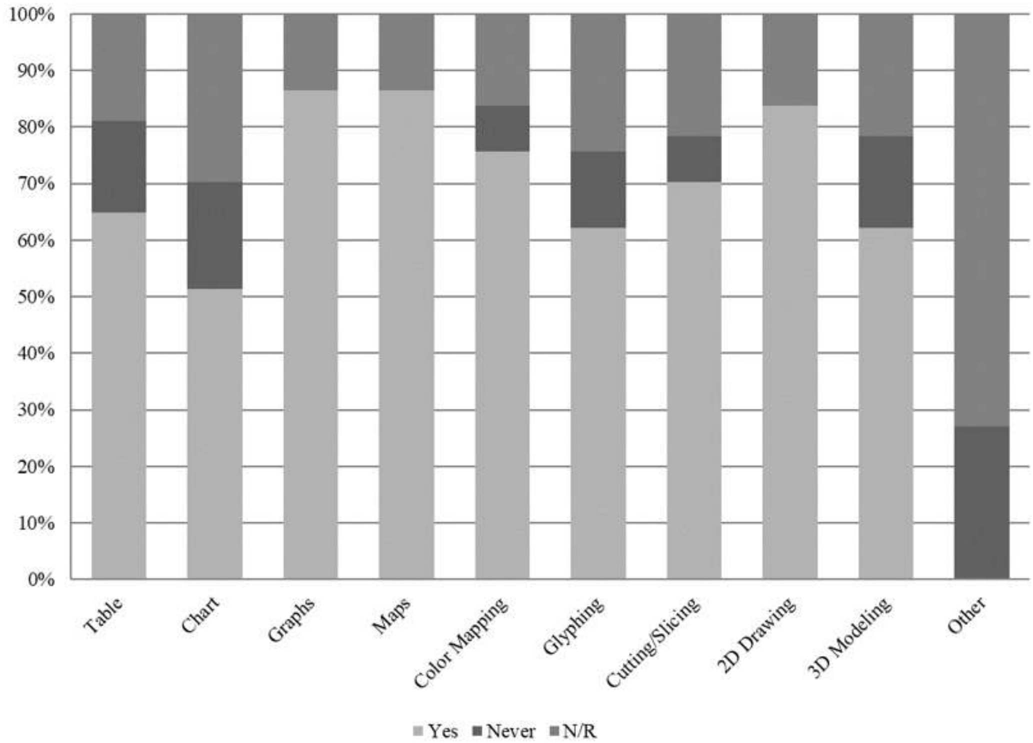


Figure 4.12: Visualization techniques

According to the received responses, archaeologists working for universities and public institutions have the same tendency: they both intensively use graphs, maps, colour mapping and 2D drawing, although with different priorities. The participants associated to private companies show a similar tendency, except for the use of colour mapping. It can be observed that there is a greater tendency of participants working in public institutions to use 3D modelling.

4.5 Summary

The survey clearly indicates that archaeologists use, to some extent, computer-based visualization methods (realistic and non-realistic). However, they still prefer traditional visualization tools. Among younger archaeologists there is an even greater preference for traditional visualization tools than among older ones. This is a curious aspect, since openness and acceptance of innovative methods or techniques are more expected among younger people. However, this is surely a precious indicator that a significant concern for visualization tools designers and developers must be to ensure an environment similar to the one archaeologists are traditionally used to.

Concerning the computer-based visualization techniques, they are more used among older archaeologists. The use of realistic and non-realistic visualization methods is not homogeneous. Younger archaeologists tend to use realistic visualization methods mostly during the archaeological process, while older ones use it more to represent archaeological entities/objects. The contrary happens with non-realistic visualization methods. Table 4.1 illustrates how visualization (both traditional and computer-based) is used in Archaeology.

		Junior	**Senior**
		Archaeologists	
Tradiditional Visualization Tools		+	-
Realistic Visualization Methods	Archaeological Process	+	-
	Archaeological Objects	-	+
Non-Realistic Visualization Methods	Archaeological Process	-	+
	Archaeological Objects	+	-
Visualization Techniques		-	+

Table 4.1: Visualization in Archaeology

Regarding the use of 3D models in the visualization of archaeological data the result of the survey raises two interesting issues: (1) on the one hand, 3D modelling is mostly used by the older archaeologists; (2) on the other hand, 3D modelling has a tendency to be more used by archaeologists that are associated to public institutions, rather than to universities. So, it is a matter to be examined more carefully in future work, particularly since 3D models are widely used to disseminate knowledge about archaeological sites among the general public.

The results of this survey noticeably show that archaeologists prefer realistic visualization methods to represent archaeological data, rather than non-realistic methods (see table 4.2). So any archaeological visualization system should contemplate these preferences in its architecture. However, according to the results of this survey, there are some aspects of non-realistic visualization that cannot be ignored, particularly as regards the use of graphs as visualization techniques.

	Realistic Visualization	**Non-Realistic Visualization**
Post Processing	+	-
Analysis & Interpretation	+	-
Research	+	-
Dissemination	+	-
Artefact & Finds	+	-
Stratigraphic Units	+	-
Structures	+	-

Table 4.2: Realistic vs. non-realistic methods

The survey analysis supports the following conclusions: (1) the traditional visualization methods still play a significant role for all archaeologists, regardless of their experience and of their expertise; (2) the archaeologists prefer simple techniques to visualize their data; (3) the archaeologists prefer realistic visualization methods to represent archaeological data, rather than non-realistic methods. Therefore, the following chapters show the author's effort to define a visualization system that uses simple technologies which are based on traditional archaeological visualization techniques and still consider the realistic representation of the data. The realistic representation is deeply connected to the use of 3D data. Thus, the next chapter will show the procedures used in this work for the acquisition of archaeological three-dimensional data, which are also extensively used at the *Archaeological Unit of the University of Minho*.

Chapter 5

Architectural and Contextual Information in Archaeological Sites

This chapter will present the visualization model that will be applied to archaeological data and suggest three visualization levels which categorise the methods that will be used to increase the perception and visual enhancement of the archaeological elements.

From the analysis of the surveys presented in the previous chapter, it is clear that archaeological data should be three-dimensional. Hence the second section of this chapter is devoted to describing the 3D data acquisition methodologies used, both for what is visible and for what is still buried. Naturally, since there is much archaeological data that are preserved in bidimensional support, the 3D restitution methodology from the existing 2D information is also explained.

5.1 The visualization model

Visualization is about transforming data into meaningful images that skilfully and truthfully express new information. Depending on the nature of the data, there are different visualization models that achieve the purpose of visualization. The visualization model that fits the three-dimensional nature of archaeological data is the *Visualization Pipeline*. This visualization model transforms the original data using encapsulated algorithms, that are consistently combined to obtain visually enhanced data [86]. This derived data is mapped on a visualization object and rendered to obtain a comprehensive image (see figure 5.1).

Besides the appropriate visualization model for the archaeological data, it is proposed to structure the visualization methodologies into three distinct and well-characterized levels. The first level introduces external elements into the visualization environment that enhance the visual perception of the archaeological element but do not interfere with the archaeological object of interest. The second level is focused on processing the geometric and/or physical properties of the archaeological element to highlight its features. The last level will not only produce additional information but also changes the geometry of the element of interest.

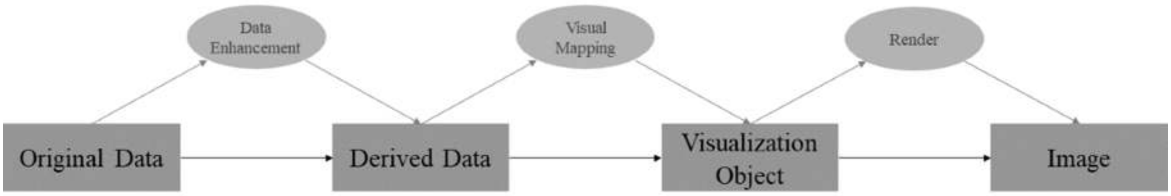


Figure 5.1: Visualization pipeline model

Each level of visualization enables increasingly more visual perception and insight into the archaeological data, due to gradually more elaborated interaction and visualization strategies (see figure 5.2). The visualization and interaction strategies are supported by annotation objects, 3D interaction techniques – that include 3D widgets and 3D sources – and 3D filters. These different elements can be used either separately or combined.

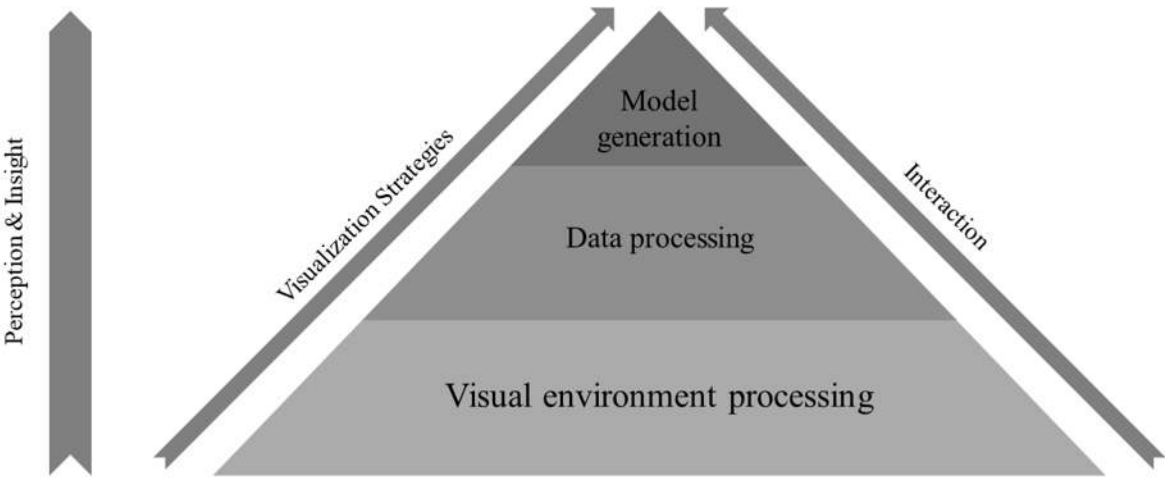


Figure 5.2: Proposed visualization model for archaeological data

In the scope of this doctoral work, it is essential to clarify the previous concepts:

- *Annotation Objects* — are entities, external to the object of interest, that assist the user to read and understand the object of interest. They provide information about a feature of the object of interest and include explanatory symbols or text that add information in the visualization environment. These elements can also be applied to 2D objects;

- *3D Interaction Techniques* — are dedicated to providing an interface between people and computers in a three-dimensional Euclidean space. These techniques will allow the user to navigate through the scene or around the object in the visualization environment using the translation, rotation, and zoom operations of the scene or object. These techniques are generally performed with the mouse device, but can be complemented with:

  - *3D Widgets* — interaction elements that are focused on selection or manipulation operations applied to 3D objects;
  - *3D Sources* — external objects that are usually associated with a 3D widget and that help the transformation of the object of interest;

- *3D Filters* — are processes designed to act on one or more 3D objects and to generate one or more transformed 3D objects. Each process is composed of one or more algorithms that transform the data regarding its geometry and/or attributes.

5.1.1 Visualization environment processing

The successful visualization of an archaeological element is primarily influenced by its visual quality and soundness which depends fundamentally on the data acquisition procedure and on the process to create its virtual representation. Archaeologists have the prompt necessity to understand the archaeological object of interest, once it is imported into the visualization environment. Therefore, assuming that the quality and reliability are assured, the global perception of the object of interest can be enhanced with straightforward annotation and user-interaction procedures.

The first visualization level comprises the use of external elements, which are not related to the archaeological data, but that complement their reading and increase their understanding. It does not modify the object of interest but increases the visual perception that the user may have about it. The main idea of this visualization level is to provide the user with an acquainted visualization environment, using extremely simple visualization methodologies, such as annotation objects and nominally demanding 3D interaction (see figure 5.3). Consequently, the visualization tools of this first level are completely data-independent and can be applied to any archaeological data – even 2D representations.

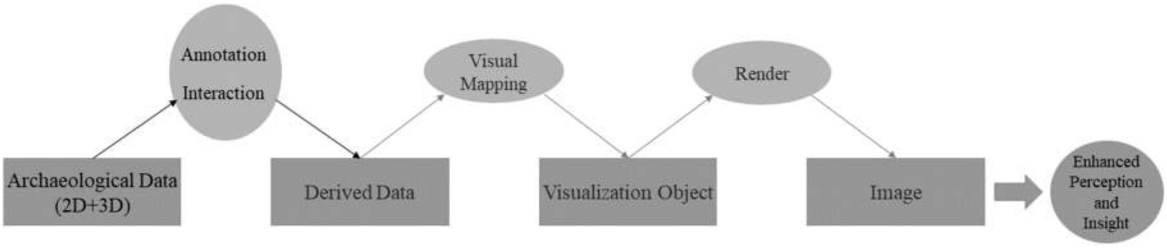
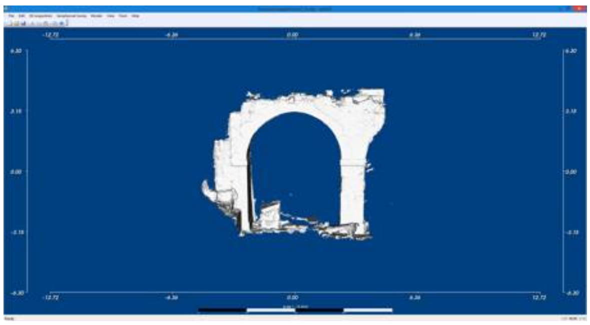


Figure 5.3: Visualization pipeline for the visualization environment processing

The example in figure 5.4a shows an archaeological element imported into the visualization environment that is easily identifiable as an arc. If a properly annotated 3D axis system is introduced into the visualization environment (see figure 5.4b), object perception is improved by understanding its orientation.

(a) Simple environment



(b) Environment with an annotation object

Figure 5.4: Visualization environment processing example

5.1.2 Data processing

For archaeologists, it is also important to recognize features or patterns on the archaeological data that will improve the understanding of these elements. However, these features and patterns are not highlighted with annotation objects and user-interaction but with filters and source objects that operate on the geometry. The use of filters is very much data-dependent, therefore, either the archaeological data is prepared to use the appropriate filters or, at least, it has to be possible to work out the data to use suitable filters.

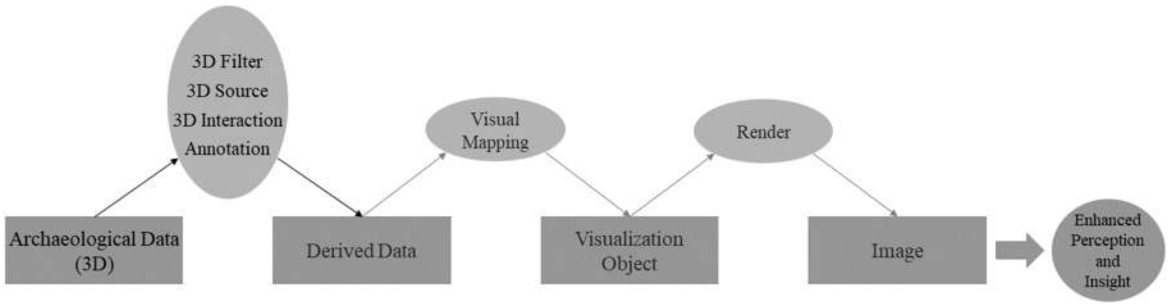


Figure 5.5: Visualization pipeline for the data processing

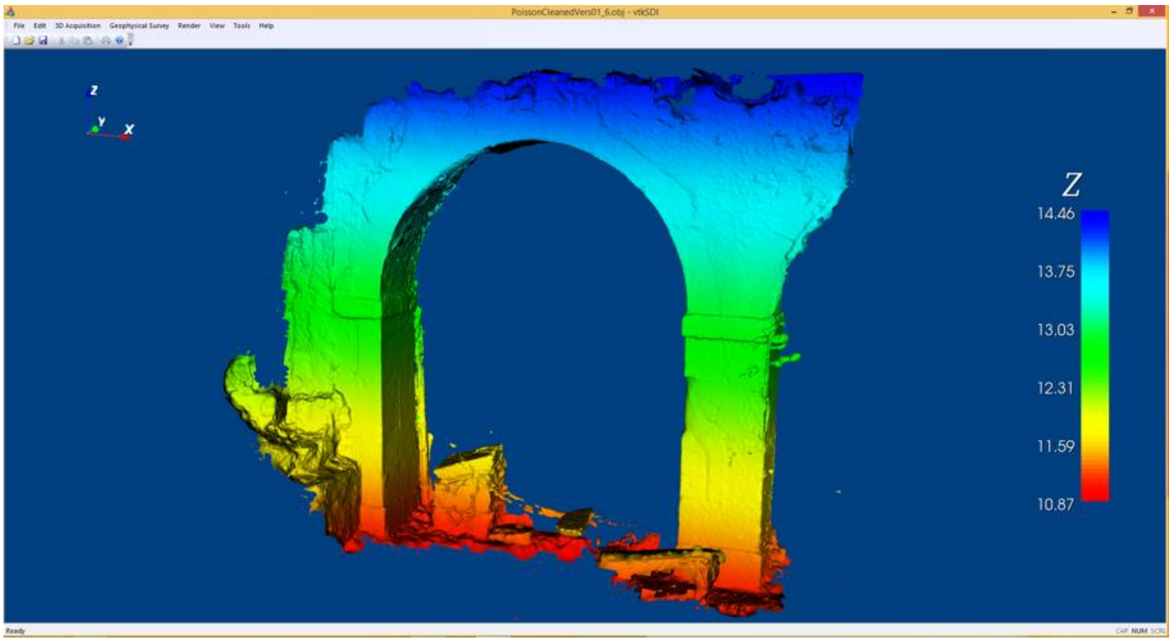


Figure 5.6: Data processing example

The second visualization level is mostly concerned about the processing of archaeological data and will not change the geometry of the object of interest, but rather highlight important information from its geometry or shape. This visualization level has to maintain the idea of simplicity, however using visualization procedures which, in addition to annotation and 3D interaction, are based on 3D filters and 3D source objects (see figure 5.5). These strategies will point out information to enhance the user's knowledge about the object. Nonetheless, while the first level of visualization is completely data-independent, the current only admits

3D representation of archaeological data.

To illustrate this level of visualization, the previous example of the arc is repeated (see figure 5.6). In this case, after applying a filter that allows colour mapping along the Z-axis and associating an annotation object that matches colours with the corresponding height (z) values, the user is able to evaluate more properties of the object.

5.1.3 Information generation

Archaeologists produce cognitive models of the past based on the data recorded during the archaeological process. Throughout the archaeological interpretation, new information is generated that is used to support the cognitive models that might be proposed for the dissemination of an archaeological site. Therefore, it is indispensable to use well-organized filters that are able to transform the original data to evaluate new information elements that might support the construction of new cognitive models.

The idea of simplicity and ease-of-use remains present in this visualization stage. In fact, the visualization methodologies continue to be based on 3D filters, 3D widgets, 3D sources, annotation objects and 3D interaction techniques (see figure 5.7). However, the aim of this level is to use more advanced procedures and perform operations over the geometry of the object to increasingly gain complete visual perception and insight. These operations should be based on the traditional archaeological procedures to analyse and interpret the data, therefore they will contribute to the deconstruction of an archaeological element and enhance the user's knowledge about it. As in the second visualization level, this level is fundamentally designed for the archaeological 3D data, which might, in some cases, have additional scalar data associated.

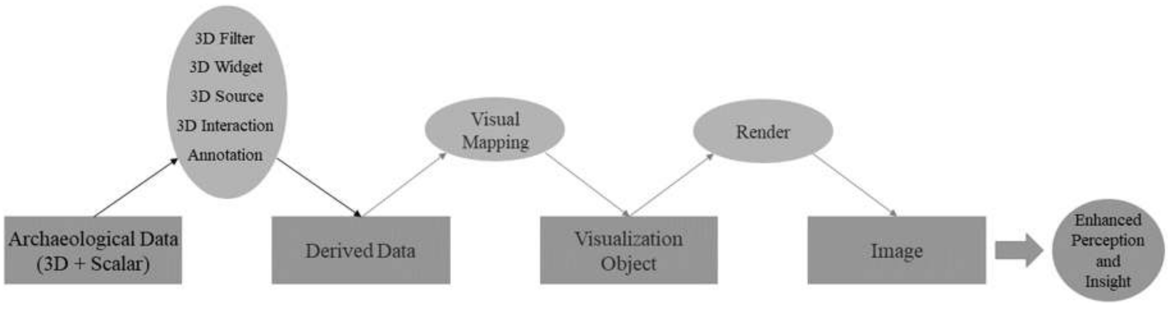


Figure 5.7: Visualization pipeline for the information generation

An example of this visualization level is the example presented in figure 5.8. Here, the user interaction utilities and the 3D filters are used to produce interactive cross-sections along the archaeological object. The result of this operation is represented as a new object which might be useful to enhance the understanding of the original object.

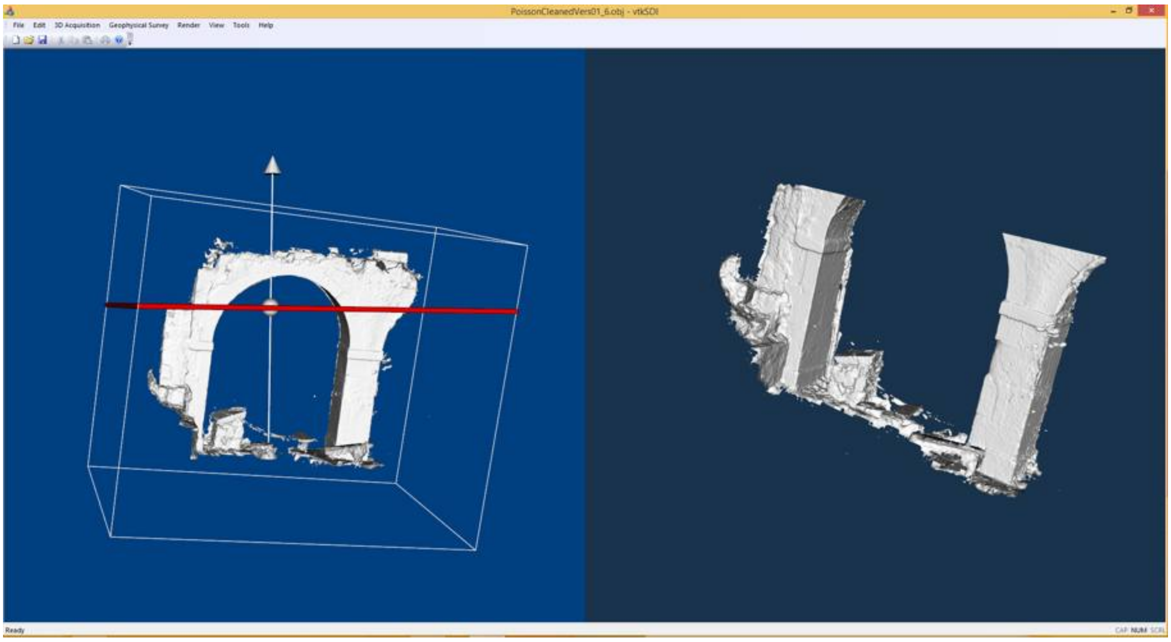


Figure 5.8: Information generation example

5.2 Data acquisition and 3D representation

The archaeological data considered within this work is classified into two distinct scales: archaeological site scale and archaeological object scale. The spatial visualization of archaeological data at a territorial scale level is undoubtedly a very important issue in archaeological research, but it will not be addressed in this doctoral work.

The archaeological data used for this work was recorded during some archaeological projects of the *Archaeological Unit of the University of Minho*. Therefore, the data was recorded using traditional data acquisition methods in archaeology, terrestrial and aerial images or *ERT* technology. Consequently, the different types of data are:

- Traditional 3D models based on *CSG* techniques;
- 3D surfaces obtained from image-based modelling techniques;

- 3D point clouds from *ERT* field survey (each 3D point has a scalar value associated, representing the electrical resistivity).

5.2.1 Traditional 3D model

As referred earlier, one of the 3D representation methodologies for archaeological elements is based on *CSG* techniques. These techniques use geometric primitives, such as spheres, cubes, cylinders or pyramids that are carefully modified with geometric transformations and *Boolean* operations to obtain the desired shape of an archaeological structure or artefact [114].

In this work, the 3D models produced with *CSG* techniques represent architectonic structures and are based on graphical and alpha-numerical information that is usually gathered in an archaeological information system. This information is compiled mostly during the archaeological record, however, some information is also available in the historical documentation used to support the archaeological process. The archaeological interpretation is also important for this modelling procedure because it generally produces graphical information that is essential to the 3D modelling procedure.

The 3D modelling process begins with a careful examination of the information elaborated during the archaeological interpretation. This information, which is traditionally on 2D support, include not only excavation plans and sections but also more elaborated reconstruction proposals of the buildings of the archaeological site. The reconstruction proposals are based on the archaeological evidence which has to be complemented with existing documentation about the place. Both, the evidence and the documentation, are extremely important to comprehend the extent of uncertainty about the archaeological elements. This analysis is crucial to understand the complexity and to establish the accuracy of the model and to set the adequate scene hierarchy.

The next step comprises the modelling of the archaeological element using *CSG* techniques. This virtual representation of the archaeological element is usually validated by experts and is often used to complement the interpretation process of the site. The realism of the final 3D model might be enhanced with textures that are assembled from previously evaluated graphics data of the historical documents or of the archaeological record. Unfortunately, there are some cases where the texture mapping procedure is not possible due to lack of information. The final and complete 3D model is often used to validate the consistency of the archaeological interpretation. Figure 5.9 illustrates the workflow used to represent the virtual 3D model of architectonic structures on archaeological sites.

These 3D models are created using 3D computer graphics software, such as *Blender* (open-source software developed by *Blender Foundation*) or *3ds Max* (commercial software from *Autodesk Inc.*). The digital models are stored in the softwares native file format and often exported as *3DS* or *X3D* (successor of *VRML2.0*), which ensures the exchangeability with visualization and dissemination platforms.

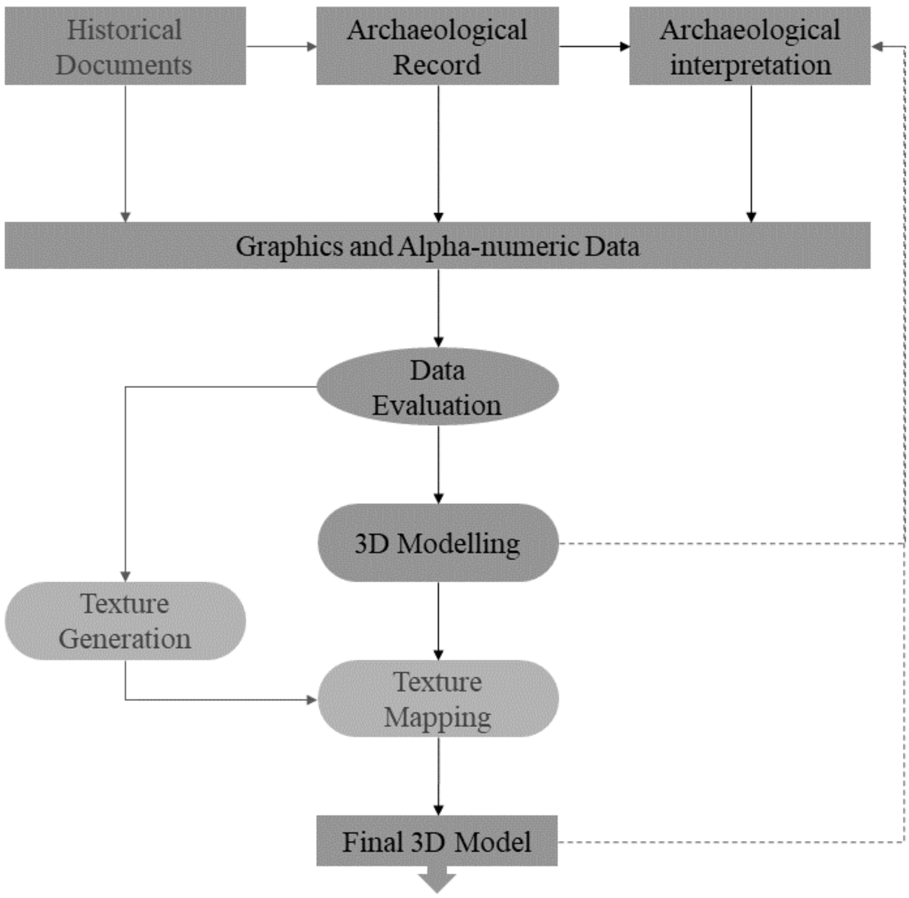


Figure 5.9: 3D modelling workflow

5.2.2 Image-based 3D data

The archaeological image-based data acquisition is carried out, taking photos from the element of interest (archaeological site or object) with a frontal and lateral overlapping of, at least, 75% and 65%, respectively. However, prior to this step, it is necessary to establish the control points associated with the archaeological entity. These control points are extremely important to ensure the exact scale, the visual accuracy and, the correct spatial orientation of the various archaeological elements. Depending on its scale, the control points are either physically marked targets, with a fixed position, placed strategically throughout the archaeological site or physical features on the archaeological object. It has to be possible to take precise measures between the various control points, to ensure the scale of the elements of interest [115]. In archaeological sites, the accuracy is preserved by using a *GPS* and/or a *Total Station* to record the exact position of the control points and to correctly measure the distance between them (see figure 5.10).

Figure 5.10: Archaeological data acquisition setup using ground control points, *UAV* and *GPS* (Courtesy of UAUM)

After finishing the acquisition in the field, the data has to be processed to generate a visually sound and precise 3D surface. The first step of this processing stage is the detection of features on the photos that are invariant to *scale*, *rotation*, *viewpoint* and *illumination*. The following step comprises the matching of the invariant features between two photos, which will be important for the sparse point cloud extraction using a feature-based bundle-adjustment algorithm. However, for detailed surface reconstruction, the initial point cloud has to be improved. This improvement can be achieved using a dense reconstruction algorithm to obtain a compact and rigorous point cloud. After a preceding point normal computation, it is possible to perform the 3D reconstruction of the acquired archaeological element using a 3D reconstruction algorithm. The obtained 3D surface can be visually enhanced by mapping a texture on the surface, which is produced from the acquired photos.

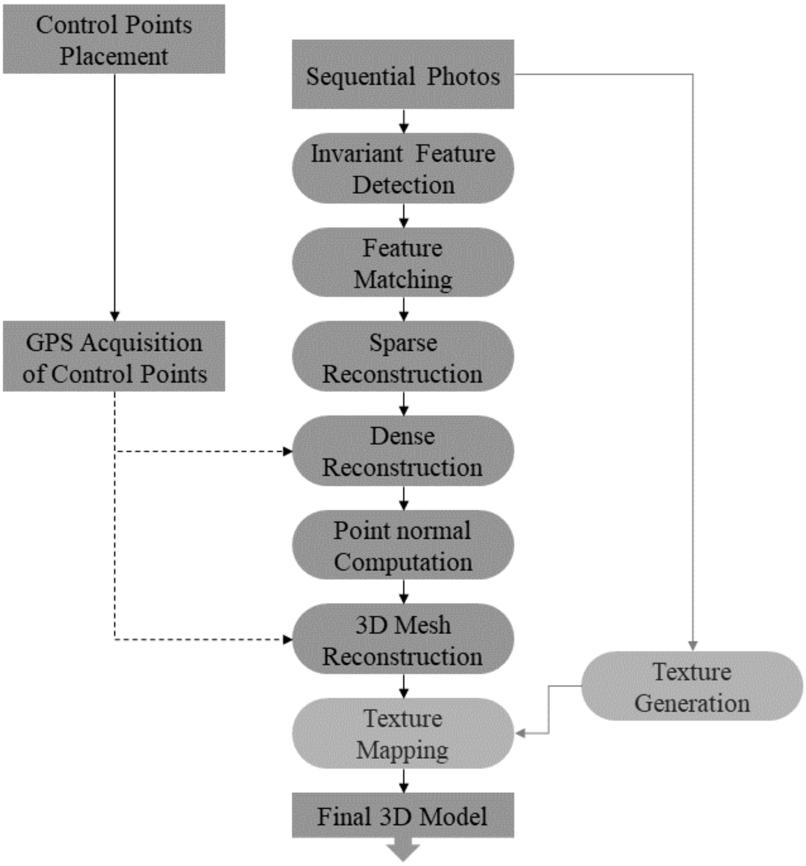


Figure 5.11: Image-based data acquisition workflow

The visual accuracy of the archaeological element can be improved by identifying the control points on the photos. While reconstructing an archaeological object the full scale is ensured by the distance measures between the various control points. However, in the case of an archaeological site not only these distance measures are necessary but also the *GPS* coordinates of each control point, which will guarantee correct georeferencing of the site. The number of control points depends on the complexity of the object of interest. In the case of the models used in this doctoral work, they vary between 4 and 10. Each control point is only useful if visible on, at least, 4 different photos.

Figure 5.11 represents the workflow used to create the image-based archaeological 3D surfaces used in this work. These archaeological elements are stored in the *Wavefront OBJ* (*.obj*) file format with an associated *Material Template Library* (*.mtl*) surface shading file [116].

5.2.3 ERT data

The purpose of *ERT* is to make electrical resistivity measurements on the ground surface, which are able to characterise the sub-surface resistivity (or conductivity) distribution. Variations in electrical resistivity are normally correlated with variations in lithology, water saturation, fluid conductivity, porosity and permeability. These variations may be used to map stratigraphic units, geological structure, sinkholes, fractures and groundwater.

Figure 5.12: *ERT* data acquisition setup (Courtesy of SINERGEO)

The *ERT* data acquisition procedure starts with the set up of the survey area with an array of regularly spaced electrodes connected to a central control unit (see figure 5.12). The data acquisition requires the injection of current into the ground using a pair of electrodes. The resulting potential field is measured by a corresponding pair of potential electrodes and recorded to build a pseudo-cross section of apparent resistivity beneath the survey line. The resistivity values are also associated with an (x, y, z) position where the value is recorded. The distance between the electrodes is set according to the aim of the survey: for archaeological surveys, the space between electrodes is small [117].

Each 3D point is georeferenced but there is no topological relation between them. They are only grouped in a uniform point cloud, where the cloud density depends on the inter-electrode spacing during the survey, which is adjusted for each site. So, it is necessary to create a perceived representation of the 3D point clouds to understand the spatial extent of the *ERT* survey and also to create topological relations between the points. An efficient approach is to use a triangulation technique that simultaneously establishes a topological relationship between the unstructured points and produces a tetrahedral mesh representing the volume of interest as a convex hull that completely bounds the surveyed points. Another functional 3D representation method is to resample the data into a volume representation, based on the scalar (electrical resistivity) values. Figure 5.13 represents the various steps that are necessary to acquire *ERT* data and to visually represent them in 3D space.

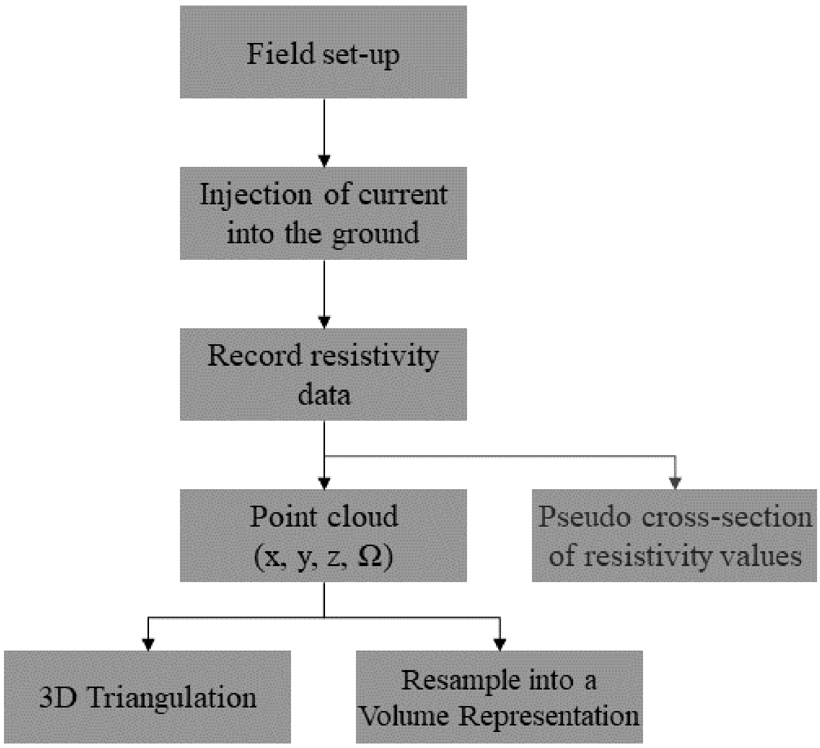


Figure 5.13: *ERT* data acquisition workflow

Chapter 6

Methods and Prototypes for Archaeological Data Visualization

This chapter will present a prototype of archaeological data visualization for each of the distinct data acquisition methodologies presented in the previous chapter. Thus, each prototype will be structured according to the visualization model presented in chapter 5 and using some of the visualization strategies presented in chapter 3, particularly the Interactive Scale Models, the Computer Graphics Rendering and the Semantically Supplemented 2D and 3D Representations.

An important purpose of each prototype is to incorporate scientific visualization methodologies that are based on the traditional practices for representing and visualizing archaeological data. These methodologies will be presented in the following section.

6.1 Visualization methods

The visualization methods have to take into consideration some characteristics of the archaeological data used to evaluate the prototypes. Therefore, it is important to consider the scale of the archaeological elements, which range from simple objects to complex sites, but also the nature of the data, whether dealing with visible or non-visible data.

However, the visualization methods do not depend only on the size of the archaeological element or on the nature of the archaeological data, they also depend, to a great extent, on the experience of the user. So, another concern is to ensure a visualization environment familiar to archaeologists. The best way to achieve this purpose is to keep the visualization methods simple but effective and similar to the traditional methodologies used to represent and visualize archaeological data.

6.1.1 Functional design

The visualization methods are based mostly on procedures that are familiar to archaeologists and, also, commonly used during the archaeological process. These methods benefit from annotation objects, 3D interaction techniques (including 3D widgets and 3D sources) and 3D filters. Thus, the visualization methods considered are:

- Orientation;
- Scale visualization;
- Colour mapping;
- Oblique lighting;
- Interpretation-free alignments;
- Triangulation-based representation;
- Volumetric representation;
- User-assisted segmentation;
- Scalar-based segmentation;
- Interactive cross-section.

Orientation

At the very beginning of the archaeological process, during the excavation phase, there is a great concern to establish an adequate orientation of the excavation grid that facilitates the reading of the archaeological site. Generally, this orientation will later be used for the archaeological illustration of the site. Also during the archaeological illustration of artefacts, it is important to decide the most important view (or views) to set the correct orientation of the object before starting the drawing. Thus, in both situations, and regardless of the different conventions and techniques used for the illustration procedure, orientation is a common principle during the archaeological record.

Similarly, in the representation of an archaeological element in a visualization environment, the orientation is essential to increase the user's ability to perceive the different views resulting from the interaction with the object. That is, when the user rotates, translates, or zooms the object, he must realize what type of view he is producing: top, bottom, side, or perspective views of the object. Thus, a simple and effective way to implement this solution is to add a three-dimensional Cartesian coordinate system to the virtual environment. The coordinate system is not associated with the 3D representation of the archaeological element, but rather with the virtual visualization environment. It will not depend on any modification operated on the archaeological element, but only on the 3D interaction (more concretely on the 3D rotation) with the object of interest. Therefore, it allows the users to continuously perceive the orientation of the object of interest and to raise its global understanding.

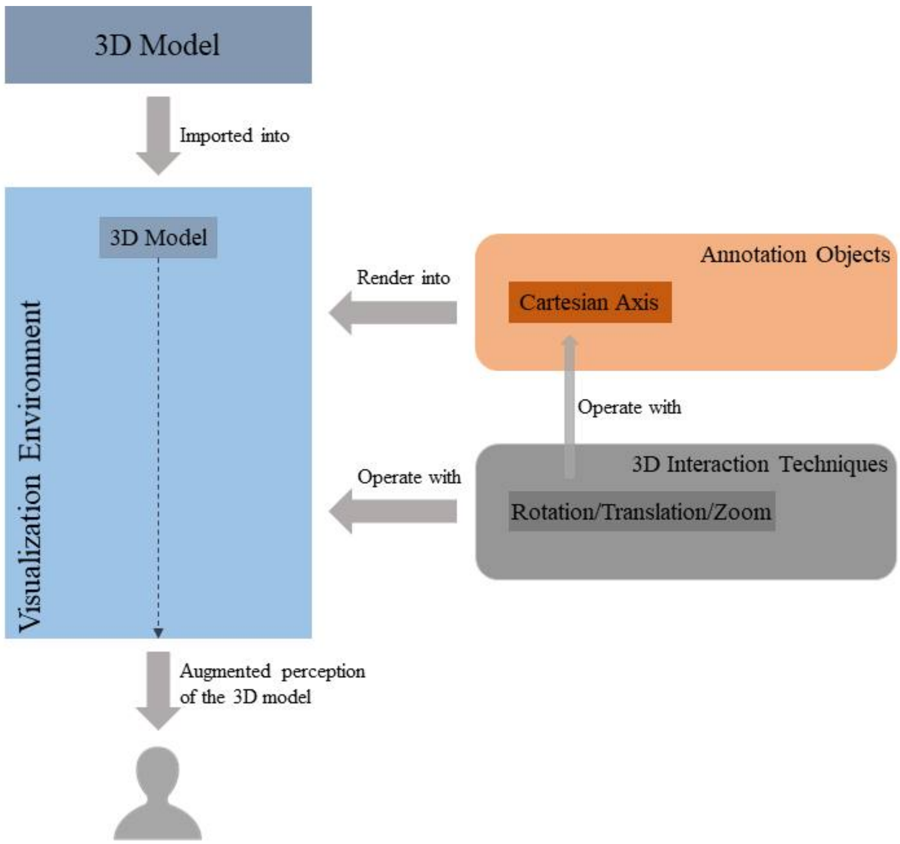


Figure 6.1: Workflow of the *Orientation* procedure

Understanding the orientation of an archaeological element is a useful step towards the analysis of its surface features. Therefore, although this orientation tool is a simple procedure, it is nonetheless crucial to understand the positioning of any archaeological element represented in the virtual visualization environment.

Considering the visualization model presented in the previous chapter, the orientation procedure belongs to the first level of the model (Visualization environment processing) and uses 3D interaction techniques and annotation objects to manipulate and improve the understandability of the 3D model, respectively. The interaction techniques, which are the rotation, the translation and the zoom, enable the user to freely operate with the global 3D scene (3D model and cartesian axes). However, it also allows the user to set up the cartesian axes, adjusting the size and the position on the render window. Besides, if necessary, the interaction operations also allow correcting the size, the position and the orientation of the 3D model. Annotation text will be used to label the perpendicular axes with X, Y and Z, representing the width, depth and height, respectively. Figure 6.1 illustrates a schematic representation of the orientation procedure's workflow.

Scale Visualization

During the archaeological record, it is indispensable to use a *graphical scale* while performing the photographic record and the field drawing of the excavation. Also, during any illustration of archaeological elements, it is essential to set the scale used to reference the drawing that is being made. The concept of *scale* is a leading principle because of its fundamental support to the analysis and representation of archaeological data. In fact, the scale of an object is always associated with the accuracy of its details. Therefore, the size of the scale is inversely proportional to the size of the archaeological element. Often, small objects have to be represented at a full or even extended scale, to ensure a detailed bidimensional representation. In this way, the inclusion of a scale in a visualization environment is necessary because it allows the user to easily evaluate the size of the object of interest, as in traditional support

Unlike the traditional paper support for archaeological illustration and drawing, the virtual visualization environment is a dynamic space and allows an intuitive and free interaction with an object through 3D rotation, zoom and translation. These operations are used for a better visual analysis of the object of interest and enable different views with changed perspectives and variable ampliation or reduction, in real-time. For this reason, the graphical scale in the virtual environment cannot be static. It must be updated in real-time to ensure the users' correct visual perception regarding the size of the object of interest. This means that the dynamic scale depends not only on the size of the object but also on the 3D interaction performed by the user.

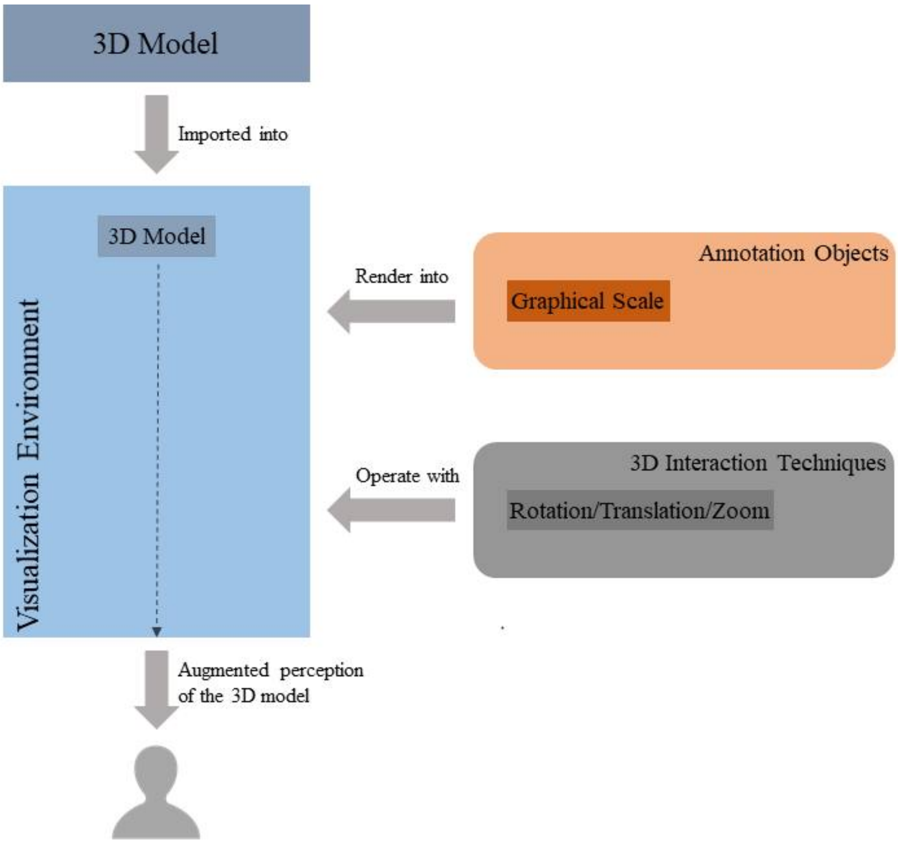


Figure 6.2: Workflow of the *Scale Visualization* procedure

Like the previous method, the scale visualization procedure belongs to the first level of the visualization model and also uses 3D interaction techniques and annotation objects. The major aim of this procedure is to have the notion of the size of the archaeological objects in the visualization environment, which is a valuable help for analysis purposes. As illustrated in figure 6.2, the 3D representation of the archaeological element and the graphical scale displayed in the visualization environment combined with the common rotation, translation and zoom facilities is a proposed procedure to improve the perception of the 3D model.

Colour Elevation Mapping

An essential attribute in archaeological research is the elevation values associated with various elements/spaces of an archaeological site. This attribute allows archaeologists to know where to position the archaeological findings, to understand the height variation within the archaeological site, as well as to find features on the site surface that allow some type of relationship (for example, spaces that are at the same level may be somehow related to each other).

If an archaeological site is represented as a virtual 3D model (either CSG- ou image-based), an effective and intuitive method of perceiving the elevation variation is to use colour mapping. This visualization method will associate one colour at each point of the 3D representation, according to the elevation value of that point. The core purpose of this colour elevation mapping procedure is to create an intuitive tool for analyzing the elevation/height values of an archaeological site or of an architectural structure. In this way, it is intended that the user is able to understand the variation of elevation throughout the archaeological site and to identify spaces that are at the same elevation/height.

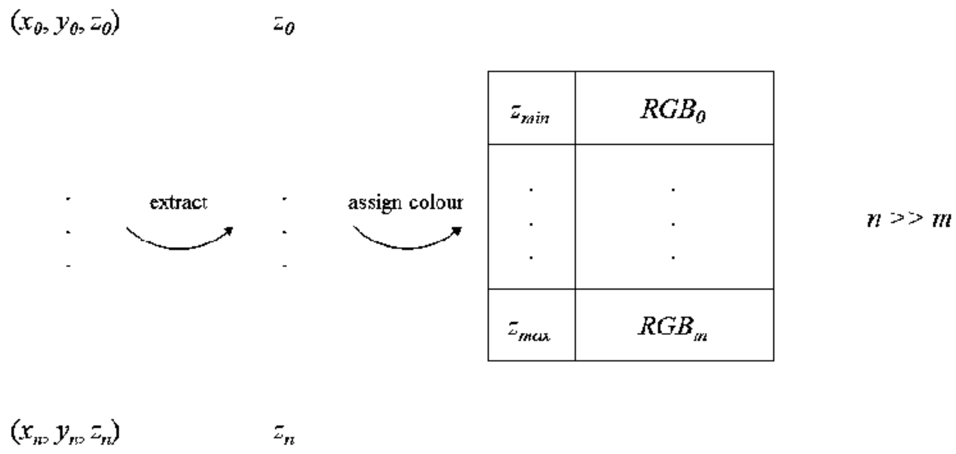


Figure 6.3: Steps to create a colour lookup table for the elevation

An efficient procedure to associate a colour to an elevation value is to generate a colour lookup table which is an extremely simple concept. The elevation is measured in the z-axis, therefore the first step is to determine the z_{min} and z_{max} of the 3D model. This range – [z_{min}, z_{max}] – will be used to build a colour lookup table, that attributes a colour to a specific scalar value (α). In this case, the scalar value is the z coordinate of each point of the 3D model (see figure 6.3).

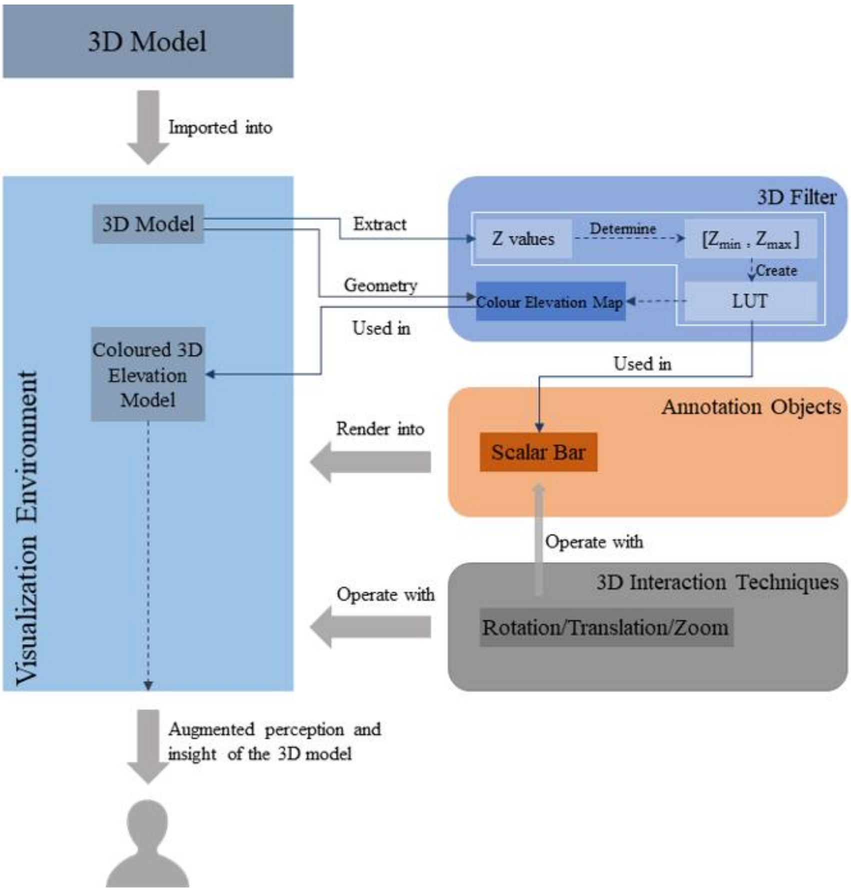


Figure 6.4: Workflow to create a coloured 3D elevation model

The subsequent phase associates one colour value from the lookup table to each data point, according to its z value. This association is achieved by checking the z value for each point and looking at the table for the corresponding colour value (r, g, b). The following step adds the colours of each z value to the mesh to obtain a visually changed representation of the original model. This new representation of the model enables a different reading of the space. The purpose of this new reading is to improve the chance for the user to identify the spaces that are at the same elevation (z value) and the comprehension of the topography of the surface. Also, to increase the understanding of the new colour-coded model the user has to recognise the elevation value through the colour. Therefore it is necessary to introduce a labelled and coloured scalar bar (annotation object) in the visualization environment that associates the colours to the elevation values. The complete workflow of this visualization procedure can be observed in figure 6.4.

The geometry of the 3D representation of the archaeological element is not changed with this procedure but the colour mapping highlights the elevation feature of the object (see figure 6.5). Therefore, the colour elevation mapping procedure fits the second level of the visualization model (Data processing). It uses a 3D filter to change the visual appearance of the initial 3D model and an annotation object to understand the alteration operated on the 3D model. The 3D interaction techniques support free interaction with the 3D model and adjust the size and position of the annotation object on the render window.

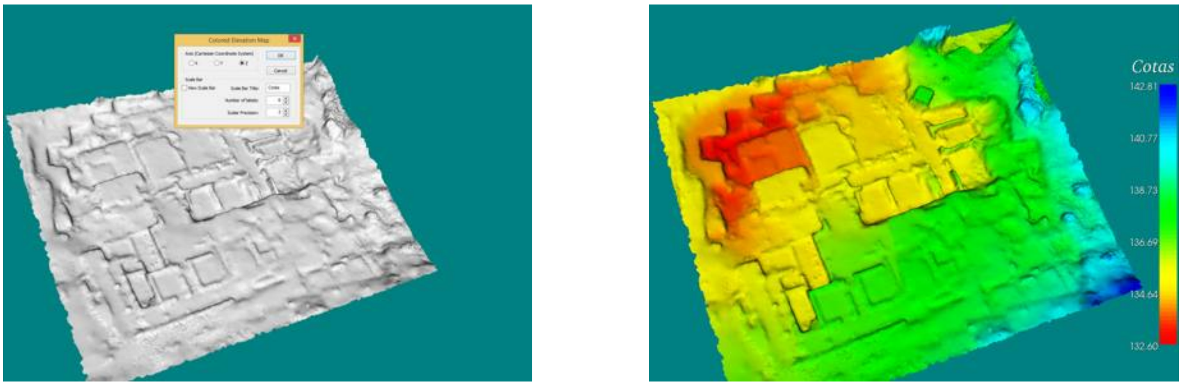


Figure 6.5: Colour elevation mapping on archaeological data

Virtual Oblique Lighting

Oblique lighting is a technique used in archaeology to enhance the visibility of objects with low relief, such as rock art carvings, fragments of surface decorated material or epigraphs, for the posterior photographic record. This technique is only used under certain conditions that depend on the materials of the archaeological elements. However, this difficulty can be overcome by using different types of light according to the type of material [118].

The concept of oblique lightning is, in some way, present in the *Reflectance Transformation Imaging* (RTI), which has been used to document cultural heritage information and to enable the generation of trustworthy digital surrogates of the real world [119]. *Mytum et al.* (2018) carefully describe this technique, that uses the *Polynomial Texture Mapping* technique (PTM) to determine the reflectance function, in [120] and explain the necessary equipment to perform such data acquisition. They also present examples of this methodology to record a range of archaeological objects with different materials, such as clay, copper, bone, glass and stone.

The results are exceptional but the entire process can be time-consuming. Also, this technique is based on images and not on 3D surfaces.

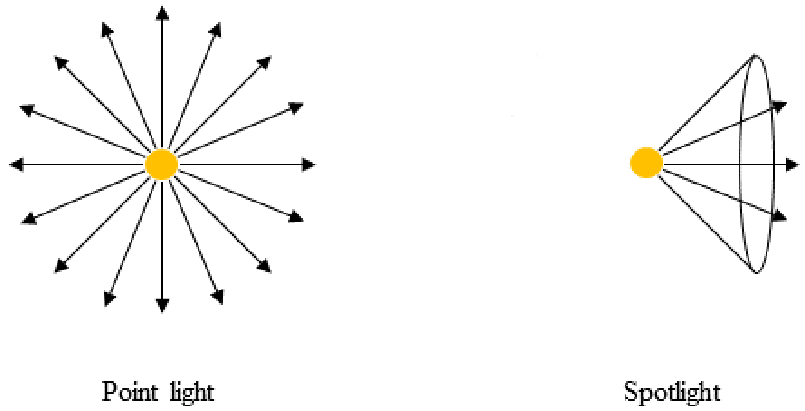


Figure 6.6: Types of light used

The virtual oblique lighting is an interaction procedure that involves the manipulation of the object that projects the light over the archaeological element. This object (3D widget) provides an interface to a more complex operation which enables an unrestricted movement around the archaeological element to be analysed. The properties of the light influence the way the user sees the 3D surface and detects its features. The type of light corresponds to a *point light* which emits light uniformly in all directions. A convenient feature of the point light is to associate a cone with limited angles that confines the light in a specific direction and transforms it into a *spotlight* (see figure 6.6). Another property is the colour of the light which can be set to any range of the *RGB* spectrum. The final property is the location of the light, which in this case will be the interactive 3D widget.

After concluding the adequate light setup the user can manipulate the interactive 3D widget around the representation of the archaeological object, examining the shadows that enhance parts of the object of interest: how the light interacts with the object, determines what is seen. The shadows that are produced will highlight low-relief features of the archaeological object and contribute to alternative readings and more complete understanding of the object.

Figure 6.7 represents the necessary workflow to produce the oblique lighting tool. After importing the archaeological element into the visualization environment, it is associated with the 3D widget. In this way, the widget recognises the object which has to be moved around.

The widgets position is used to position the light source and the centre of the bounding box that surrounds the archaeological element is used as the focal point of the light. Moving the widget will produce different shadows on the archaeological object.

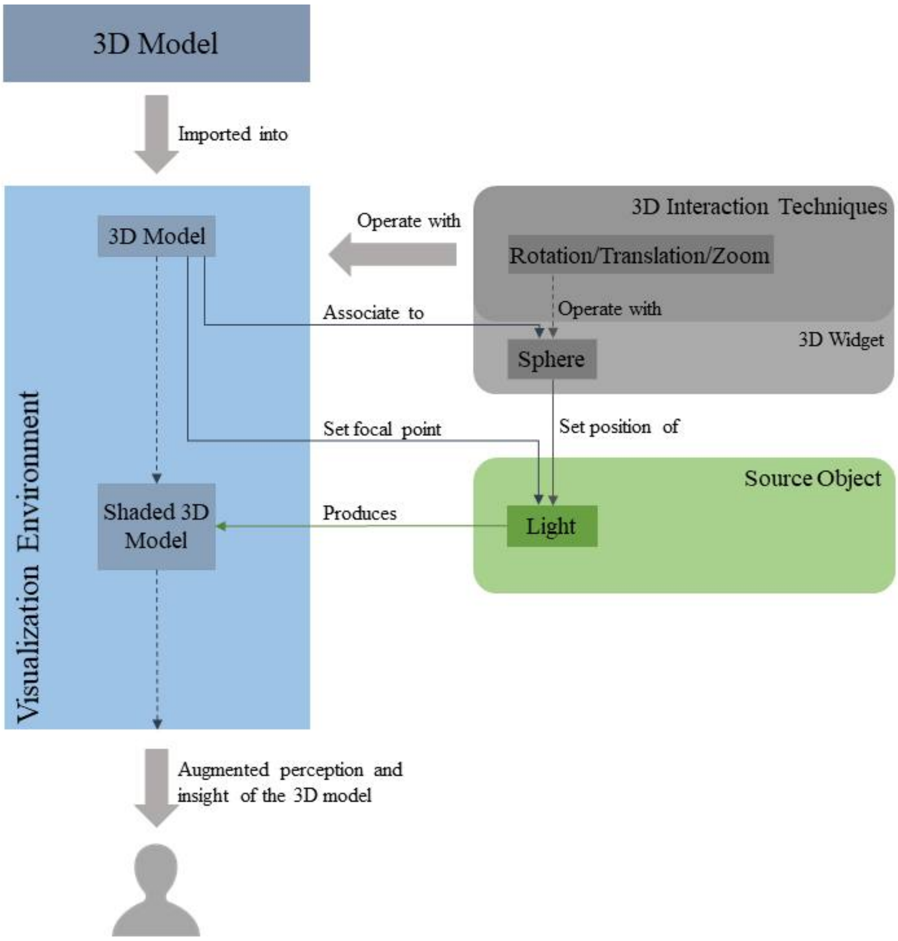


Figure 6.7: Workflow of the virtual oblique lighting procedure

The idea behind simulating oblique lighting in a 3D visualization environment is to create different visual perceptions of the archaeological object in order to reveal essential features on the surface that otherwise are less perceptible. These features are extremely important for the analysis and interpretation of the object of interest. Neither the geometry nor the material properties of the 3D mesh that represents the archaeological object will be altered. Therefore, this procedure belongs to the second level of the visualization model and associates a source object (light) to a 3D widget (sphere) which operates over a 3D model to get augmented perception and additional insight of the archaeological element. Figure 6.8 exemplifies a concrete situation of using this visualization procedure to enhance the visibility of an epigraph in data referring to a follow-up excavation in the historical centre of Braga.

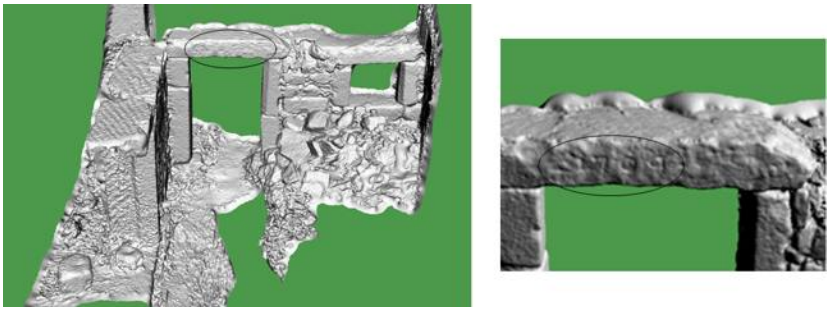


Figure 6.8: Oblique lighting used to enhance an epigraph over an entrance

Interpretation-free Alignment

Alignment is a widely used concept in archaeology to find possible relationships between distinct archaeological elements of a site or landscape. The determination of these relationships contributes positively to the analysis and knowledge of these spaces. Generally, the archaeological alignments refer to collinear arrangements of structures, or other archaeological elements, that can be observed in the site or in the landscape. In the context of the archaeological site, these alignments are generally used to help define a site plan. Thus, the main objective of this procedure is to create interpretation-free alignments from 3D meshes representing an archaeological site.

The archaeologists establish alignments on archaeological sites according to the observation of the space and their professional experience. These alignments are usually influenced by the material evidence and their understanding of the site, therefore an archaeological plan of the site results, mostly, from an interpretation. However, the interpretation of an archaeological site is often a time-consuming task and the first archaeological plan is often an urgent necessity. Therefore, the initial production of an interpretation-free plan of the site is certainly a valuable help to speed up the creation of a first rigorous plan of the site.

The idea behind the interpretation-free plan of the site is to automatically detect natural alignments from well-defined structures in the site. The total set of alignments will represent the initial interpretation-free plan of the site.

The automatic generation of lines, applied to areas such as scientific illustration, artistic expression of entertainment graphics, has been since ever an important subject in computer graphics research [121]. Therefore, there is a great variety of non-photorealistic methodologies that can be applied to obtain edges that represent the feature lines of the surface. In the current context, the technology used is *silhouette* technology.

The *silhouette* is a traditional illustration technique for representing objects or scenes as solid *shapes*. These shapes are obtained by projecting the *shadow* of an object or scene on a bi-dimensional surface. The shape depends on the position of the light source and the edges of the shape represent the *outline* of what is being represented. According to [122], there are many hypotheses about the origin of this technique, but it is certain that its use was intensified, during the 18th and 19th century, mainly to produce artistic portraits [123]. Silhouettes are still intensively used in media art and illustrations. The concept is also employed, for quite some time, both in Computer Vision and Computer Graphics, where it is used, for example, to overcome difficulties related with shape and object recognition [124] and also to produce computer-generated non-realistic technical illustrations of 3D objects [125], respectively.

The archaeological sites are here represented as polygonal meshes, therefore the silhouette determination model used has to find the silhouette lines along edges that lie on the border between changes of surface visibility. However, silhouette detection algorithms applied to polygonal meshes can be distinguished between image space algorithms (only operate on image buffers), object space algorithms (silhouette represented by an analytic description of silhouette edges) or hybrid space algorithms (manipulation in object space, but produce the silhouette in an image buffer) [121]. The interpretation-free plan of the archaeological site has to be represented as an analytic set of edges with exact precision, therefore it is most adequate to use the object space algorithms to determine not only the silhouette but also the creases and the borders of the archaeological site representation. The principle of object space algorithms applied to polygonal surfaces comprises two basic stages:

- Classification of all polygons of the mesh as front or back-facing;

- Selection of all edges that simultaneously share one front and one back-facing polygon.

The complete workflow to create an interpretation-free plan, based on alignments can be seen in figure 6.9. This visualization procedure starts with the detection of feature lines on the surface of the 3D mesh that represents a virtual model of an archaeological site. A feature line is a credible set of edges from the 3D mesh that helps to define the shape of an object. The following step groups all these feature lines into an independent object, which will embody the initial uninterpreted plan of the site. This initial plan, while rendered as an isolated object, is also a non-photorealistic representation of the site. Therefore, this strategy should assist the superimposition of the plan over the 3D surface representation to evaluate the accurateness of the interpretation-free plan.

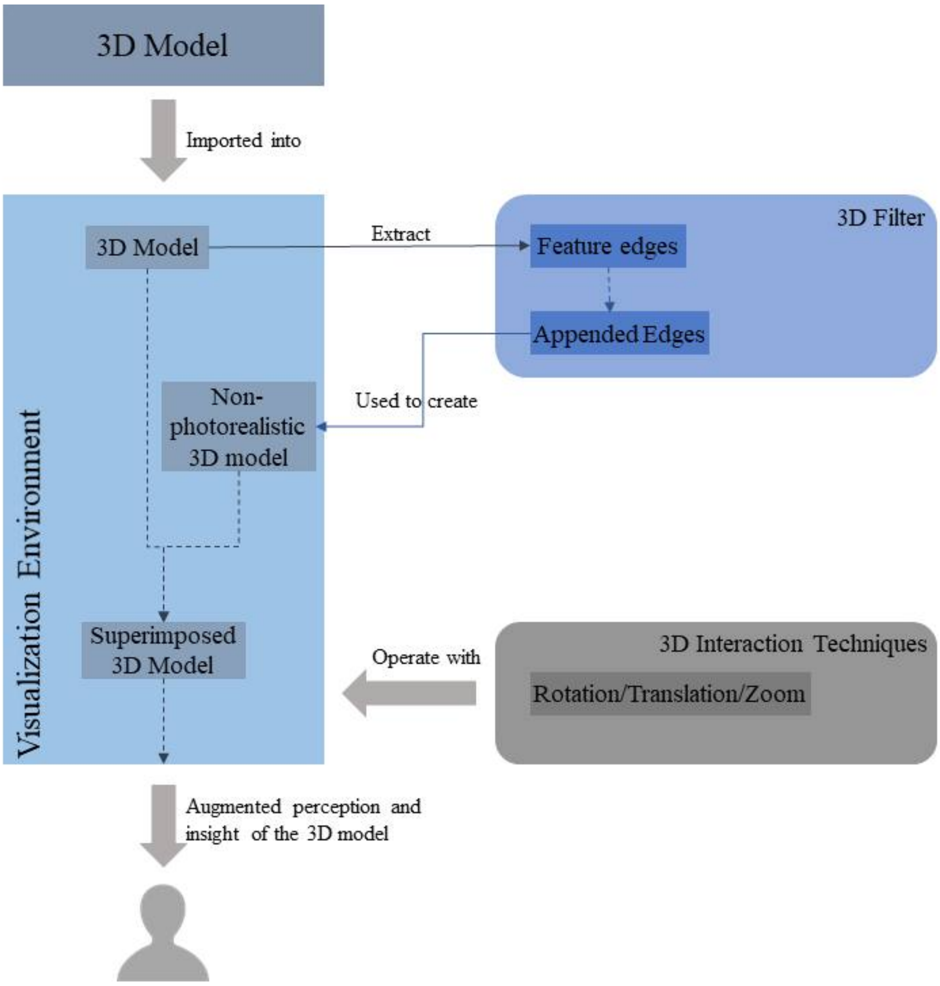


Figure 6.9: Workflow to create an interpretation-free plan

The interpretation-free alignment procedure produces a new non-photorealistic 3D model from the initial representation of the archaeological data (see figure 6.10). Therefore, considering the visualization model defined in the previous chapter, this procedure belongs to the third visualization level of the model and uses a 3D filter to transform the initial data into a complementary 3D representation that values the understanding of the archaeological element.

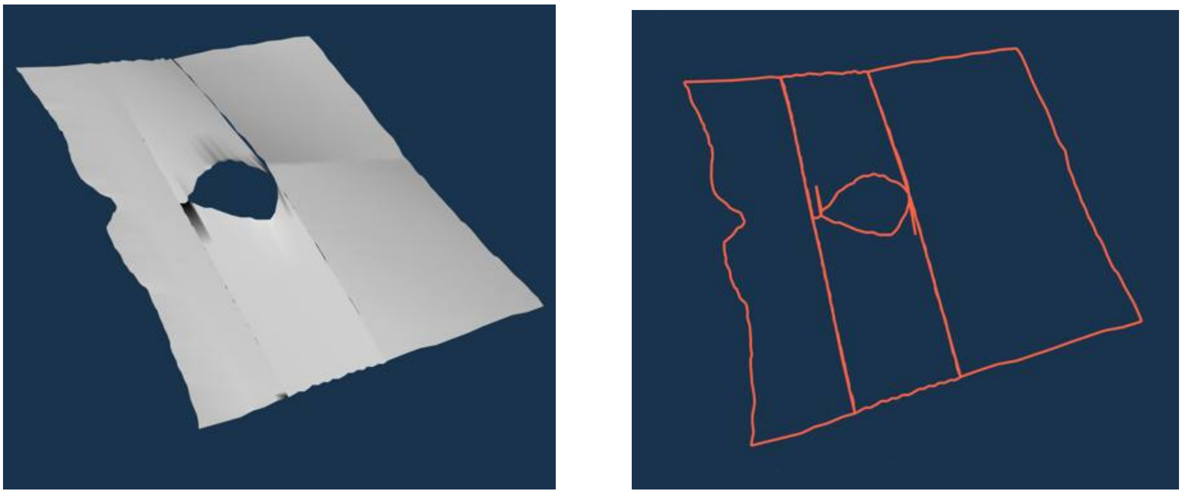


Figure 6.10: Interpretation-free alignment of archaeological data

Data modelling

The data modelling procedure is necessary to visually understand the shape of the region which was surveyed using ERT technology. There are two major approaches considered:

- Triangulation technique;
- Resampling on a volume dataset.

Triangulation The 3D points from the ERT survey have a scalar value (the electrical resistivity) associated, but no topological relation between them. Therefore, an appropriate method to produce sound topological relations between the points is the 3D Delaunay triangulation, which also ensures well-shaped triangles with large internal angles, that are important for a balanced rendering [126][127].

The result of the 3D Delaunay triangulation is a tetrahedral mesh which represents the outer contour of the surveyed volume. This output enables subsequent processing to improve the surface appearance of the mesh. Figure 6.11 explains how the ERT 3D point cloud is transformed into a volume with potential archaeological interest. Figure 6.12 exemplifies the different stages of the triangulation procedure: (a) *point cloud* representation before the triangularion procedure; (b) *wireframe* and (c) *surface* model representation after the tiangulation.

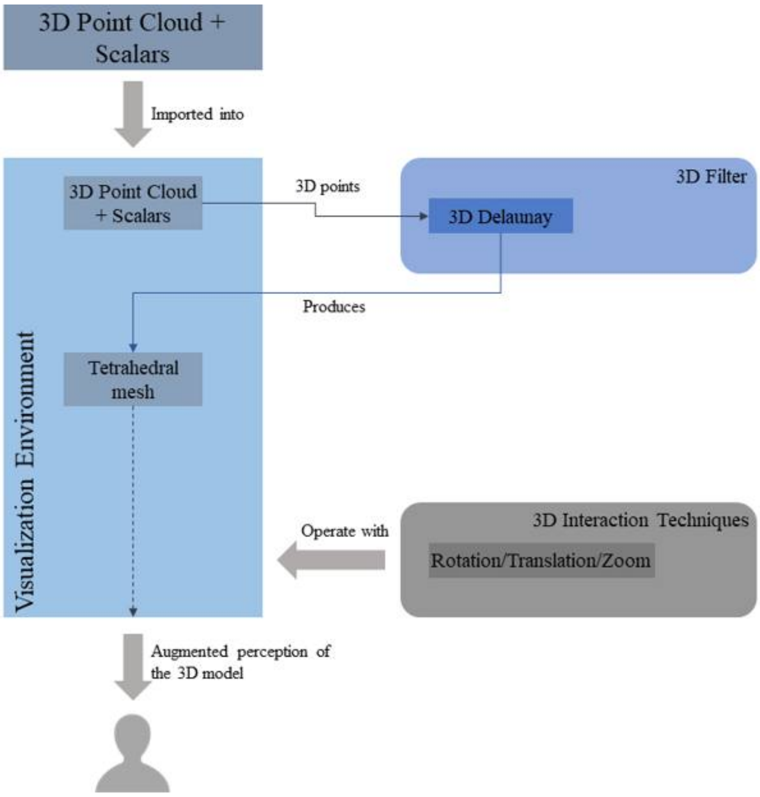


Figure 6.11: Workflow of the triangulation procedure

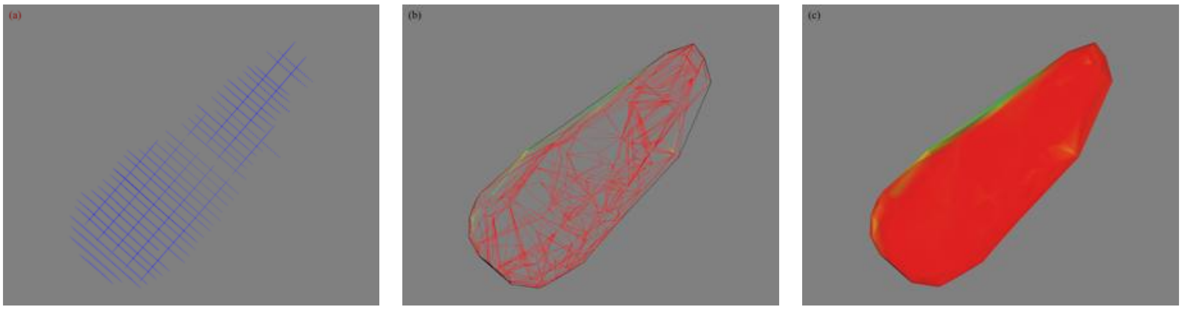


Figure 6.12: Triangulation of ERT data

Volume representation An alternative and complementary method to represent the point cloud is to resample the 3D points on a volume dataset using Shepard's method. This method is an operator that uses a set of points with no structure or order between their relative locations and produces a 3D volume [128]. The perception of the volume is increased using colour and opacity, associated to each scalar value. In the case of the ERT surveyed data the colour and opacity mapping is based on the resistivity ($\Omega.m$) values.

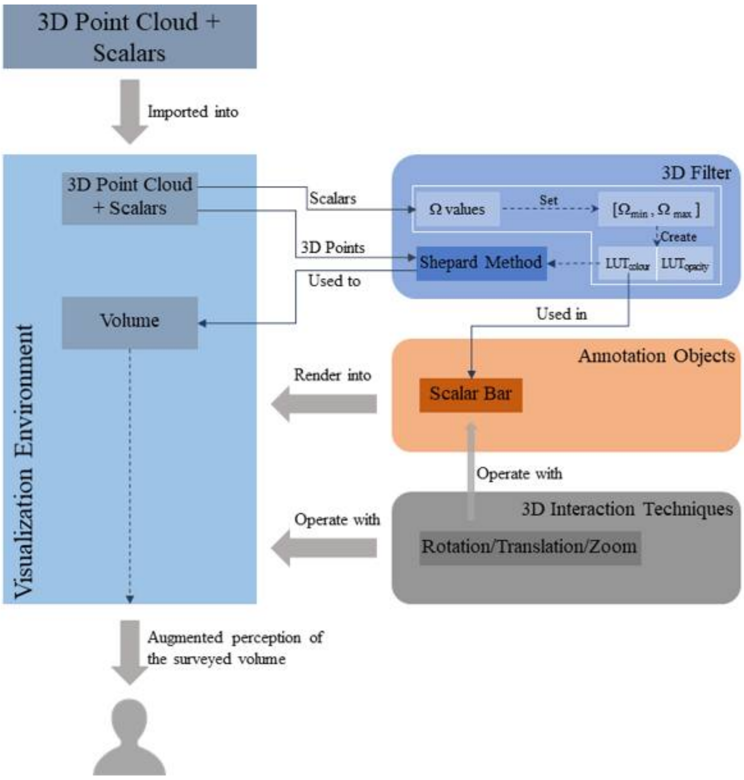


Figure 6.13: Workflow to create a volume of archaeological interest using Shepard's method

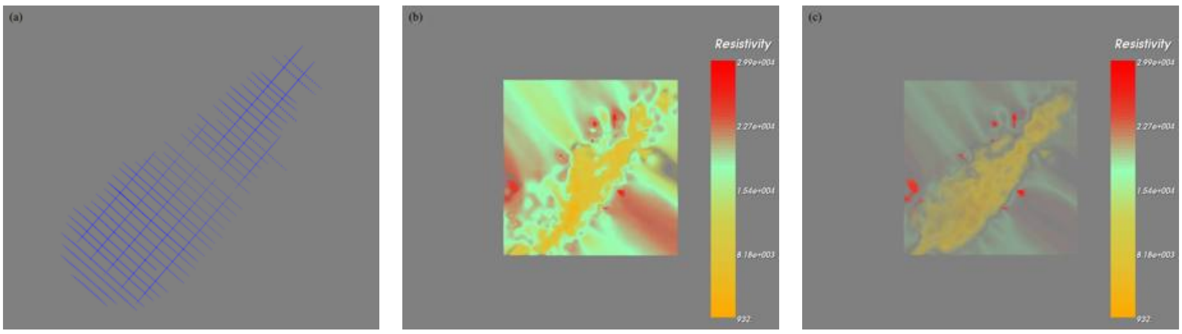


Figure 6.14: Volume representation of ERT data

The colour and opacity mapping is performed with two distinct lookup tables. The adequate setup of these lookup tables is a major issue and depends on the correct understanding of the meaning of the resistivity values. The truthful volume visualization is influenced by the ability of the user to chose the correct range of resistivity values with archaeological interest. Figure 6.13 illustrates the complete workflow to produce a volumetric representation of the ERT survey, highlighting the volumes with potential archaeological interest. A practical situation is exemplified in figure 6.14: the initial point cloud (a) is transformed in to the volume representation (b), which can be improved by setting up the colours and the opacity values (c).

Data Segmention

The segmentation of archaeological data consists in the subdivision of the 3D geometry into smaller elements which either have a specific function or uniform visual properties. It is a very significant process for the understanding of archaeological elements and a transversal subject to the different archaeological scales.

On the one hand, in the case of archaeological artefacts, for example, this process is important to detach relevant features from the shape or to isolate different functional elements. On the other hand, in archaeological sites, it plays a fundamental part in the definition of stratigraphic units which is an important concept in Archaeology to understand the occupation of the site. The interpretation of an archaeological site depends to a large extent on the ability of the archaeology team responsible for the site to recognize and carefully delineate the different stratigraphic units that characterize the site.

User-assisted mesh segmentation The archaeological 3D representation based on *CSG* techniques usually does not have the need for segmentation because they rely on already interpreted and segmented data, which generally do not require further classification. Therefore, the segmentation process makes perfect sense and is extremely useful to create the first effort of surface classification on archaeological data represented by 3D meshes. In this sense, the principal objective of this data segmentation procedure is to permit the user to delimit and extract regions of interest from an archaeological element represented as a 3D mesh.

The segmentation of 3D meshes can either be performed manually or (semi-)automatically. For the latter ones, there is a great variety of segmentation algorithms, carefully described in [129], that are applied to meshes. Some of them are even applied in the cultural heritage field [130], however, due to the geometric complexity of some archaeological elements, there are still some difficulties regarding accuracy [131]. The segmentation of archaeological data is also an interpretation, therefore, the user-assisted segmentation is a valid method to ensure higher accuracy in the segmentation procedure.

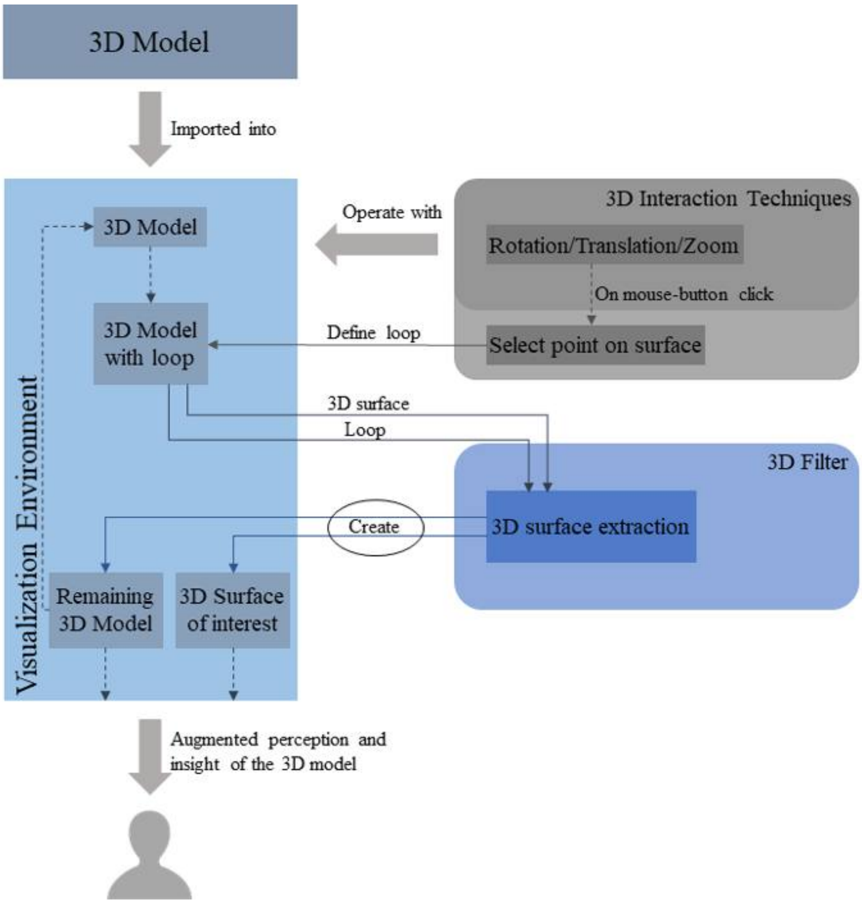


Figure 6.15: User-assisted Segmentation Workflow

The strategy in the case of the user-assisted data segmentation involves two distinct steps. The first step comprises the definition of a region of interest on the surface of the archaeological elements 3D representation. This region of interest may either represent a feature of an archaeological artefact, or a stratigraphic unit of an excavated area. Nevertheless, the idea in any of the situations consists in selecting the points that form a non-intersecting loop that delimits the region of interest on the 3D surface. The second step is to remove the selected region from the initial surface. In this way, the surface corresponding to the region of interest is obtained, while the remaining surface can continue to be segmented until the required regions of interest are reached. The workflow of this manual segmentation procedure is presented in figure 6.15.

The user-assisted segmentation procedure produces new geometric models from the initial representation of the archaeological element, using 3D interaction techniques to define the area of interest and a 3D filter to extract the defined area from the original 3D model (see figure 6.16). This procedure belongs to the third level of the visualization model.

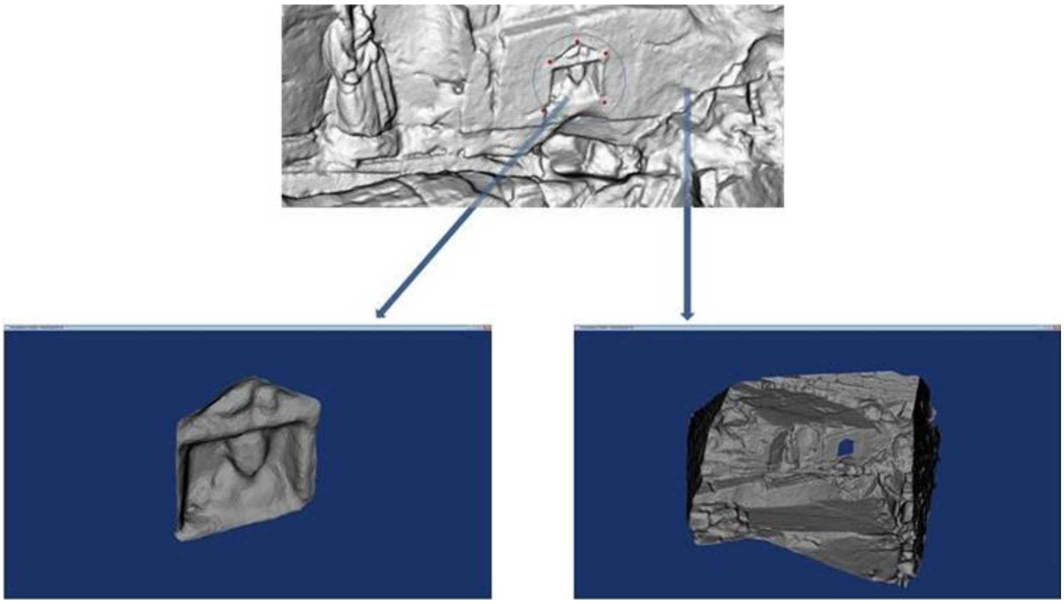


Figure 6.16: Users-assisted segmentation example

Scalar-based point cloud segmentation The purpose of the scalar-based segmentation procedure is to create coherent volumes associated with a range of previously determined scalar values. The idea is to separate the points related to scalar values of interest from the initial point cloud and cluster them into a comprehensible 3D volume. The scalar values associated with the 3D points are physical properties – in this case, resistivity values obtained during an ERT survey – that might relate to archaeological features.

The scalar-based point cloud segmentation process (see figure 6.17) starts with the definition of the scalar value or range, which represent classes of resistivity values with eventual archaeological significance. The methodology consists in separating the points related to scalar values of interest from the initial point cloud and cluster them into a comprehensible 3D volume. This extraction is accomplished by contouring the classes. The contouring procedure efficiently constructs a boundary between these classes.

The current segmentation method, which is based on a contouring algorithm (a 3D filter), produces clusters (see figure 6.18) based on the scalar values that might have an archaeological interest. This method belongs to the third level of the proposed visualization model.

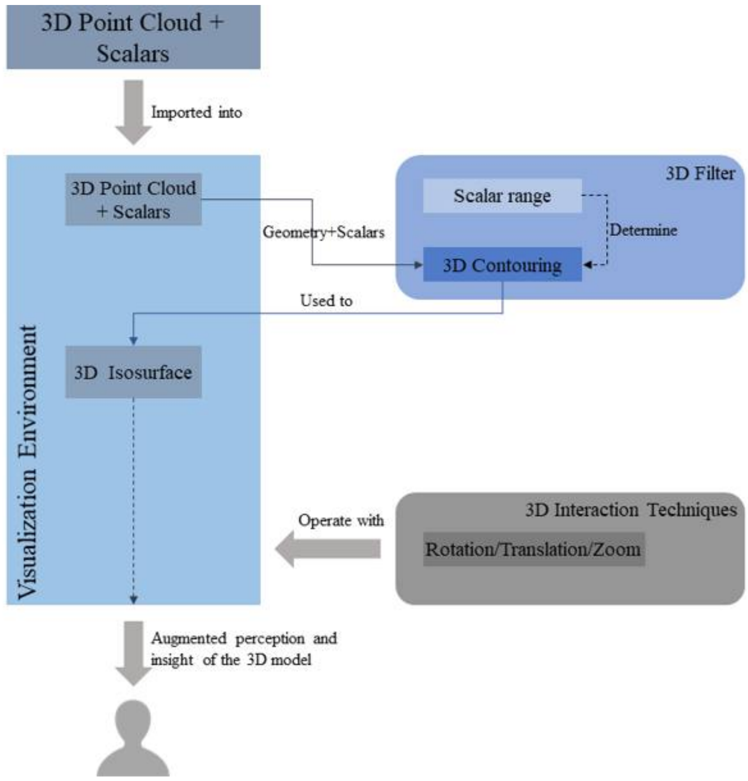


Figure 6.17: Scalar-based Point Cloud Segmentation Workflow

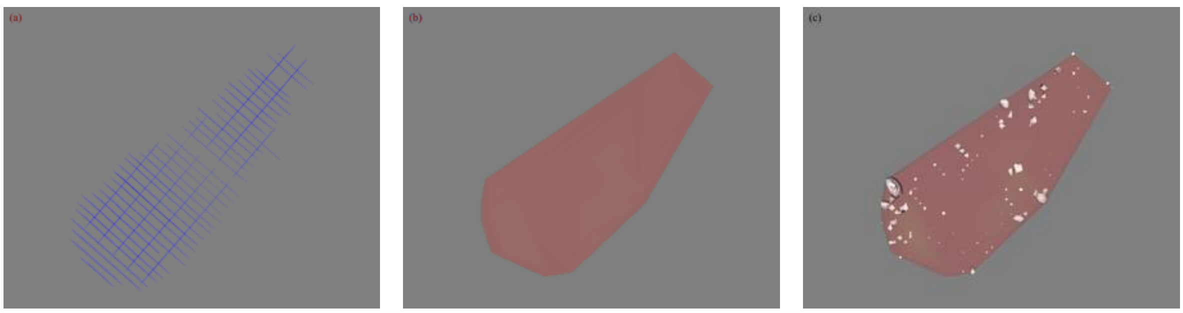


Figure 6.18: Scalar-based segmentation example of ERT data

Interactive cross-section

The traditional section drawings in archaeology are measured drawings of vertical cuts through layers and structures on excavations, that are useful not only to record areas of complex archaeology but also to understand the site. This kind of drawings is often used to analyze reconstruction proposals of a site or a building, based on archaeological data and they are also important to analyse pottery or even lithic artefacts, to comprehend its morphology and use. Therefore, section drawing is a concept that is widely used in archaeology both for understanding a site, a building or an artefact, and used in different phases of the archaeological process. However, notwithstanding the enormous importance of sections in the study of an archaeological site or in the analysis of ceramics or lithic elements, the difficulty in producing a section constrains the number of available sections.

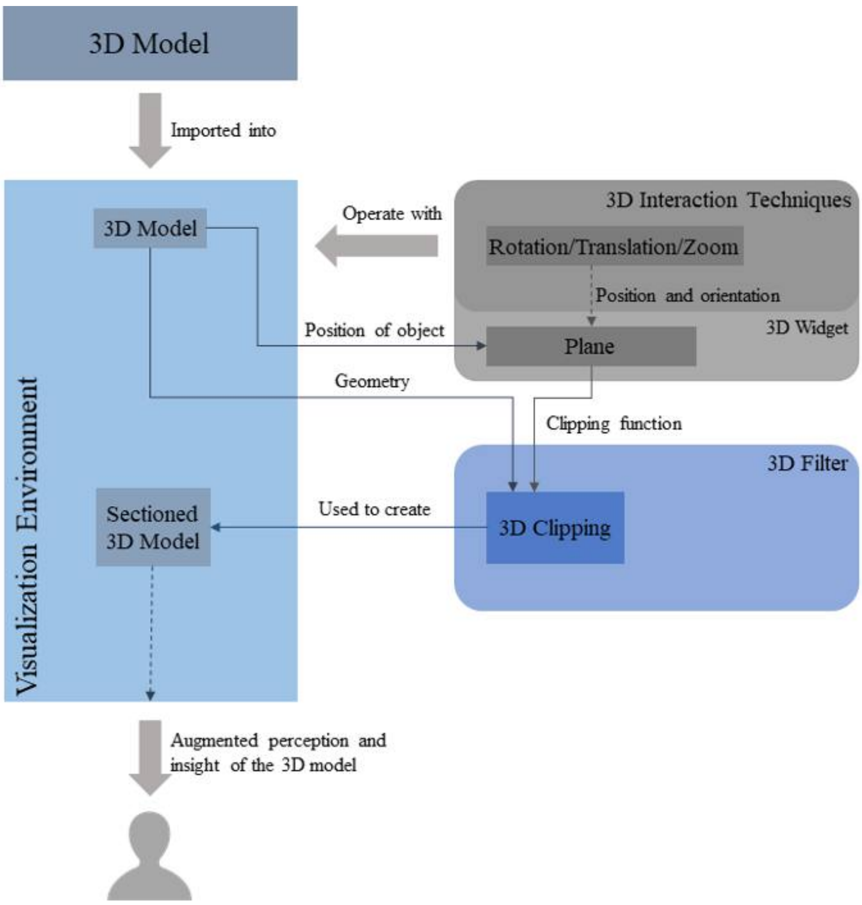


Figure 6.19: Interactive cross-section workflow

The basic idea behind a section drawing is to define a view of what is considered to be important for archaeological record or for building analysis purposes, position a vertical plane conveniently, and project on the previous plane all the visible archaeological information on that view. This same principle can be adopted in the virtual visualization environment, either using a cutting or a clipping procedure, to obtain a vertical reading of the archaeological 3D data. The main difference between these two procedures is that a cutting technique generates a cross-section through the 3D data while a clipping method creates a volume of interest limited by a clipping function. This means that by using clipping methods the three-dimensionality of the initial data will be preserved.

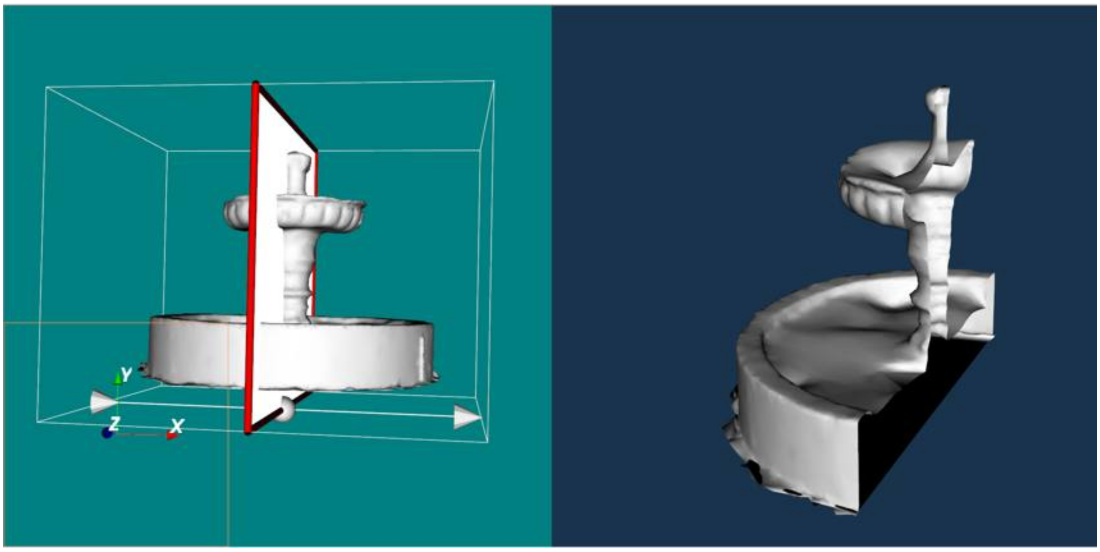


Figure 6.20: Interactive cross-section example

The objective of the interactive cross-section procedure is to execute arbitrary sections on an archaeological 3D model. This procedure starts by defining a clipping plane that limits the volume of interest which will be analysed. The next step involves the definition of a clipping procedure linked with the plane that eliminates the part of the object that is beyond the clipping plane. The last phase is necessary to ensure interactivity, therefore it consists in associating the clipping plane to a 3D interactive widget. By freely moving around the object of interest, it is possible to create, in real-time, various vertical sections of the archaeological element. Also, since the plane is associated with a 3D widget that can be freely rotated, it is possible to generate sections of horizontal and oblique reading. The complete workflow is represented in figure 6.19.

Regarding the suggested visualization model, this procedure has its place in the third visualization level, since it uses an interactive 3D widget that is associated to a 3D filter (clipping algorithm) to produce a section of the initial 3D model (see figure 6.20).

6.1.2 Implementation

There are several commercial and open-source visualization systems that might be used for visualizing archaeological data. However, the proposed visualization methodologies were implemented using the *Visualization Toolkit* (VTK) from *Kitware Inc.* [132] , which is an open-source software system. VTK supports a great variety of visualization algorithms and interaction techniques and it is available for different platforms, such as *Windows*, *Linux*, *Mac* and, more recently, for mobile devices.

6.2 Visualization prototypes

This section will present three distinct visualization prototypes for archaeological 3D data. The prototypes were defined taking into account the nature and complexity of the 3D data representing the archaeological elements. Consequently, the prototypes will handle:

- 3D models based on archaeological interpretation — The purpose of this prototype is to evaluate and extract information from 3D models that result from the analysis and interpretation of the archaeological site record (normally, 2D archaeological drawings and photography and alphanumeric information);

- 3D mesh from image-based archaeological record — The image-based surface of an archaeological element is an extremely accurate geometric 3D representation which is not classified or segmented. Therefore, the main objective of this prototype is to analyse the 3D mesh and recognize helpful features to improve the understanding of the surface. Another aim of this prototype is to help the user in the classification/segmentation process of the surface;

- ERT-based 3D point cloud (each point has an associated scalar value) — The first objective of this last prototype is to create a perceived spatial representation of the 3D point cloud. The ERT data has an additional attribute associated to each point which is the resistivity, represented as a scalar value. So, the subsequent purpose is to create representative clusters of potential archaeological features by analysing the resistivity values and determining a range of interest.

6.2.1 Prototype Architecture

The architecture of the three prototypes is similar and comprises a visualization environment that graphically represents the imported archaeological data, the annotation elements associated with the data, the tools for interaction with the 3D models and the changes that are operated on those models. It further contains a set of modules that transform the data to become more understandable by the end-user and to increase the insight of the archaeological element that is processed.

The modules that integrate the visualization system architecture are:

- *Data exchange* module — the data interaction module is responsible for importing data representing archaeological elements and takes into account the three distinct types of data used to represent the archaeological record. The 3D data processed by this visualization system might be exported to a suitable 3D format (typically, the OBJ file format).

- *Modelling* module — this module is only used if the 3D data corresponds to a regularly spaced point cloud, with scalar information associated with each point. The modelling module creates one or more volumetric representations of the point cloud, which can be used separately or combined.

- *3D filter* module — this module transforms the visual appearance of the initial data in order to highlight relevant information that contributes to the increased knowledge of the archaeological element. This transformation can only be performed either on the physical characteristics of the object (e.g. colour, transparency, etc.) or on the geometry of the object (e.g. new objects with geometry distinct from the initial one).

- *Annotation* module — this module is responsible for creating annotation objects that are introduced into the visualization environment to increase understanding and/or support the analysis of archaeological elements.

- *3D interaction* module — the 3D interaction module is responsible for manipulating objects (3D model or annotation objects) in the visualization environment and for providing objects that will transform the appearance or geometry of the initial models (3D widgets).

The visualization process of archaeological data begins immediately after the data is imported into the visualization environment. The user then complements the viewing environment with an annotation object to increase understanding of the object under analysis. From this point on, the user can customize the 3D filters to analyze the archaeological element in detail and to gain more insight about the object. All manipulations are ensured by 3D interaction techniques. A previous volume modelling process must take place if 3D points are imported. All this workflow is illustrated in figure 6.21.

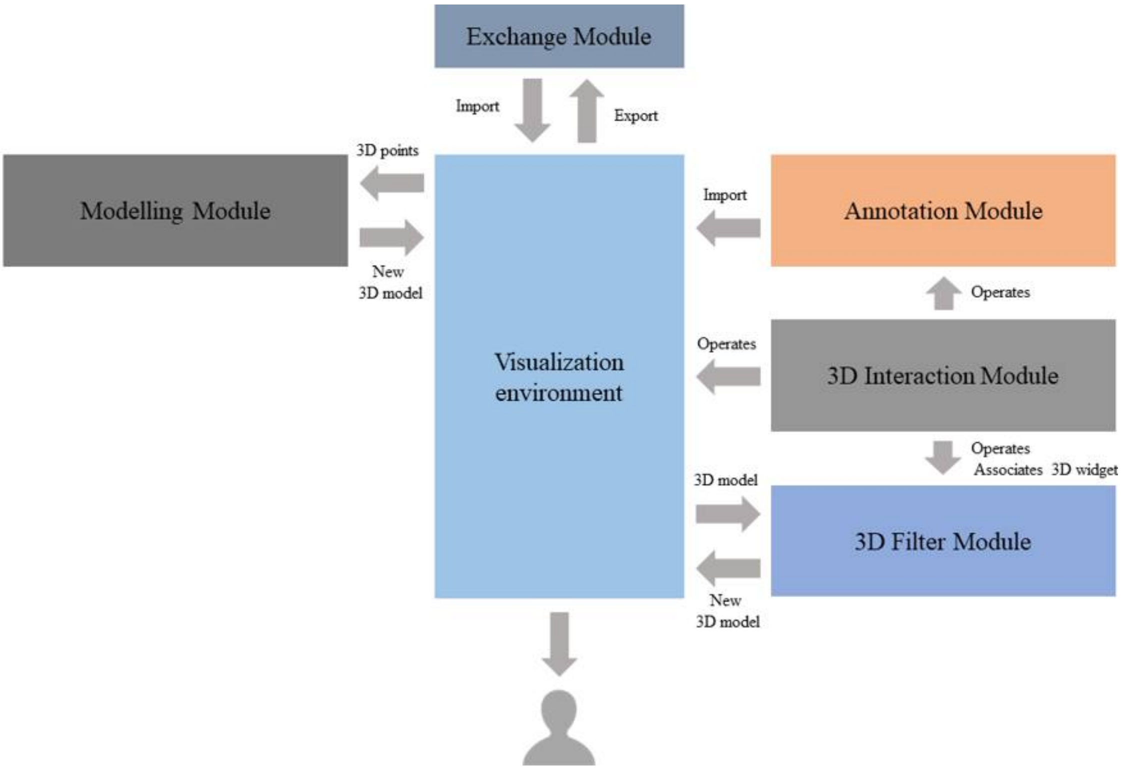


Figure 6.21: Architecture of the visualization system

6.2.2 First prototype: interpretation-based 3D models

The visualization procedures associated with this prototype must allow the deconstruction of the virtual model to better analyze the cognitive model that led to the virtual representation. The fact that these models result from the analysis and interpretation of archaeological data suggest that its 3D representation is accomplished with multiple objects. These several objects obey to a scene structure that is preserved when imported into the visualization environment.

The deconstruction of the virtual model is executed using the 3D interaction techniques such as the rotation, translation and zoom. The orientation procedure and the dynamic scale procedure are two simple visualization procedures that are part of this prototype to enhance the global perception of the 3D model. Another important procedure is the interactive cross-section tool that is able to generate on the fly several cross-sections that assist the user in the analysis of the virtual representation of the archaeological element.

6.2.3 Second prototype: image-based 3D mesh

The 3D reconstruction based on images generates a unique triangular mesh that does not have any associated additional information. Thus, the visualization methods associated with this prototype will operate only on the geometric properties of the 3D surface. The visualization methods that are included in this prototype are the orientation and scale procedure to increase the overall understanding of the 3D model. Furthermore, to process the geometry of the object for additional classification and/or segmentation, the prototype includes:

- the colour mapping procedure;
- the virtual oblique lighting procedure;
- the interpretation-free alignment procedure;
- the user-assisted mesh segmentation procedure;
- the interactive cross-section procedure.

6.2.4 Third prototype: ERT-based 3D point cloud

The third prototype includes several of the proposed visualization methods:

- The orientation method;
- The dynamic scale visualization method;

- The modelling procedure
- The scalar-based segmentation method;
- The interactive cross-section procedure;

The first two methods are used to understand the positioning and the dimension od the archaeological element, while the modelling procedure is included to ensure the spatial representation of the data and to visually understand how the resistivity is distributed. The scalar-based segmentation procedure and the interactive cross-section procedure are also part of this prototype to generate and to increase the perception of the clusters, respectively.

6.3 Summary

	First prototype	**Second prototype**	**Third prototype**
Orientation	+	+	+
Dynamic scale	+	+	+
Colour mapping	-	+	+
Oblique lighting	-	+	-
Interpretation-free alignments	-	+	-
3D Triangulation	-	-	+
Volumetric reconstruction	-	-	+
User-assisted segmentation	-	+	-
Scalar-based segmentation	-	-	+
Interactive cross-section	+	+	+

Table 6.1: Use of the suggested visualization methodologies in the different prototypes

The table 6.1 shows the use of the different visualization methodologies mentioned above in the three implemented prototypes. The visualization methods associated with the first level of the visualization model are common to all prototypes, while the methods of the second level are fundamentally used by the prototype concerned with the visualization of image-based 3D mesh. The visualization methods that are related to the third visualization level are fundamentally used by the second and third prototypes. However, the interactive cross-section procedure is common to all prototypes.

In the next chapter, the three prototypes will be evaluated regarding the usability and the capability to produce new understanding about an archaeological site or object. Each prototype will be assigned to one or more archaeological element and specific tasks will be established for experts to carry out.

Chapter 7

Evaluation of the Prototypes

The three visualization prototypes were tried out with archaeological data recorded at different sites of different nature and geographically located at the municipalities of Braga and Boticas (North of Portugal – see figure 7.1). In both municipalities, the archaeological intervention was entrusted to the *Archeology Unit of the University of Minho* (UAUM). However, the archaeological work was performed by different teams of archaeologists. The data used in each prototype included a virtual 3D model produced from the traditional data acquisition procedures and the archaeological interpretation of the site, 3D surfaces obtained from image-based 3D reconstruction and a 3D point cloud acquired during an ERT survey of an archaeological site.

Figure 7.1: Localization of the archaeological sites considered within this work

The archaeological interventions of Braga were carried out within the scope of the *Bracara Augusta* Project (Roman name of the present city of Braga), whose scientific direction belongs to the UAUM. This project emerged in 1976 as the first urban archaeology project in Portugal and it is the only one that has remained active until the present. The use of digital support for excavation records began in 1992 with the creation of an archaeological information system that facilitated the cross-checking of data from different archaeological interventions and allowed for faster access to information, integrated management and rapid dissemination. Later, in 1998, the first 3D virtual reconstructions of the Roman city (with particular focus on some buildings) was proposed, based on the archaeological interpretation and supported by the archaeological information system [133]. The prototype evaluation will use data from three excavations (see figure 7.2) accomplished in Braga for the *Bracara Augusta* project: (A) the *domus* of Carvalheiras, (B) the *thermae* of Alto da Cividade and (C) the Fonte do Ídolo.

Figure 7.2: Archaeological sites associated with the *Bracara Augusta* project, used in this work: A - The roman *domus* of Carvalheiras; B - The *thermae* of Alto da Cividade; C - The Fonte do Ídolo

The archaeological work performed in Boticas was prepared in the context of the collaboration protocol between the University of Minho and the municipality of Boticas, that aims at the development of an archaeological study regarding the settlements and landscapes in the Upper Terva River Valley (*PoPaTerva* Project), whose scientific coordination was assigned to the UAUM. This project focuses on distinct layers of the landscape structure so the research has been carried out at a cross-platform level, integrating knowledge and techniques from Archaeology, Paleoenvironments, Geophysics, Geothermal Hydrology, Biology and Tourism [134]. The prototype evaluation uses the archaeological data coming from two sites (see figure 7.3) that are part of the Terva Valley Archaeological Park: (A) Souto Escuro 1 and (B) Sapelos Hillfort.

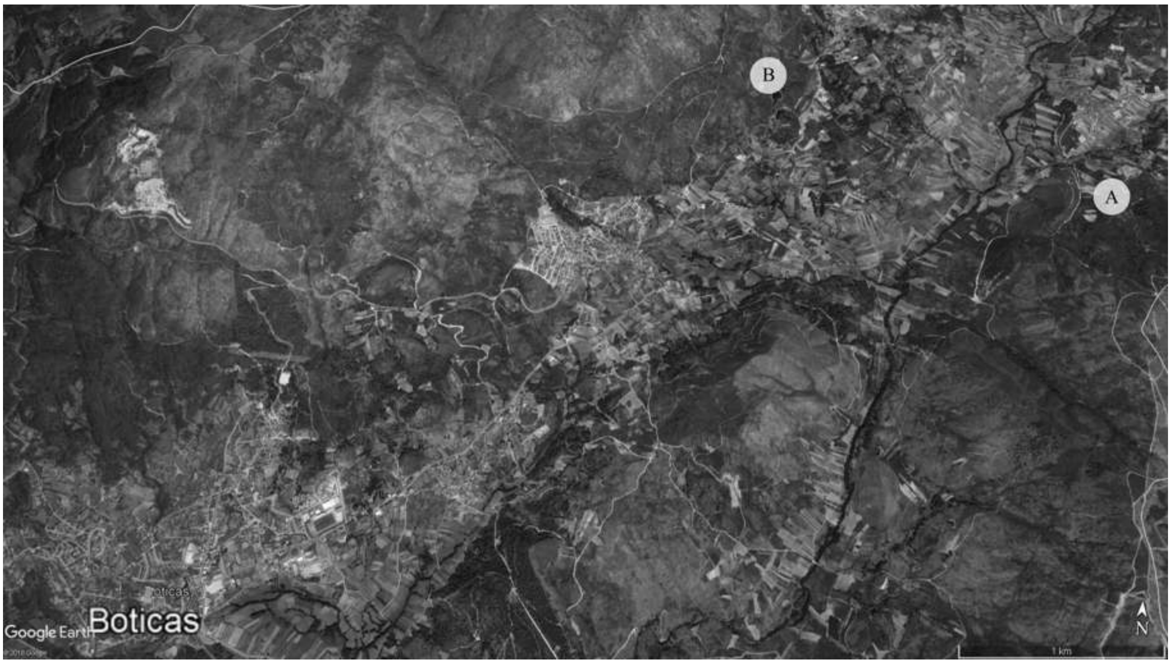


Figure 7.3: Archaeological sites associated with Terva Valley Archaeological Park, used in this work: A - The Sapelos Hillfort; B - The Souto Escuro 1 rock art site

7.1 The first prototype

The purpose of the first prototype is to get complementary insight from a 3D model based on the traditional archaeological record that already was carefully analysed for archaeological research. Over the past 20 years, the UAUM has led many projects where such 3D models have been supportive in disseminating archaeological research. As part of the *Virtual Bracara Augusta* project, some models with high interest for research were produced [135], so the evaluation of this prototype will use the 3D model of the Roman *domus* of Carvalheiras.

This prototype was evaluated by two archaeologists with distinct professional backgrounds. The first (Archaeologist A) is an archaeologist with extensive knowledge of the site and professional experience of 15 years. The second (Archaeologist B) is an archaeologist who does not know the site well. He has 20 years of professional experience and some practice in developing mobile applications for archaeologists.

7.1.1 The Roman *domus* of Carvalheiras (Braga, Portugal)

The archaeological excavations carried out over 20 years at the urban area of the Carvalheiras in Braga (Portugal) uncovered a *domus* that occupies an entire block of the city of *Bracara Augusta* [136]. The *domus* of the Carvalheiras is located in the northwest quadrant of the city (see figure 7.4), near the *forum*. This architectonic structure has an area of about 1152 m^2 and consists of a housing with *atrium* and a peristyle, flanked by porticos and neighbouring streets, whose planimetry has been completely recovered.

Figure 7.4: The ruins of the *domus* of Carvalheiras

Given the size of the house and its infrastructures, the *domus* of Carvalheiras will probably have belonged to a wealthy family from *Bracara Augusta*. Since it is a fully excavated Roman house in the city of Braga, it is considered as a prototype of the elite urban housing of *Bracara Augusta* in the Upper Empire. It is a private building from the Flavian period (second half of the first century) and provides the archaeological researchers with precious elements that value the domestic architecture in the context of daily life and sociability in the Roman cities of the north-west area of the Iberian peninsula. A comprehensive and rigorous analysis of this Roman private building can be found in [137].

7.1.2 Virtual representation of the site

The rigorous knowledge regarding this architectural structure supported the 3D representation of its two distinct constructive phases. The work of Silva (2000) presented in [138] was an indispensable source to assist the traditional 3D modelling procedure in the representation of the two phases of the structure.

The modelling process started with the representation of the floor of the building, using the information of the plans and the elevation values. The following step was the modelling of the interior and exterior of the building, still based on the interpreted plans. This step was completed also with the information of the facades and sections, that enabled the representation of the windows, doors, columns, the support structure of the roof and the roof itself. These models do not include textures since they represent restitution of something that is not visible. Hence, by choice, the different constructive elements of the house were attributed only a distinctive colour, according to what is the knowledge of housing nuclei of this kind.

The final model was processed with *Blender 2.60* and exported to *VRML 2.0* format, preserving all the features of the global scene. In this way, the model was ready to be imported into the visualization environment to be analysed by experts. The virtual model representing the first phase of the *domus* of Carvalheiras is composed of 71.395 vertices and 136.528 faces.

7.1.3 3D interaction

After importing the 3D model into the visualization environment, it is possible to interact either with the whole scene or with some selected objects that compose it. The simple manipulation that allows general observation is ensured by the 3D interaction module. This module enables to choose either the *camera* or the *object mode*, which controls the whole scene or only a specific object of the scene, respectively.

The interaction is performed simply with the mouse and has two different style options (*Joystick* and *Trackball*). The *joystick* style causes continuous actions when the mouse keys are holding down, while the *trackball* style causes actions only when the mouse is moving and the keys are pressed. The 3D axis, which can be placed and arbitrarily sized up on the visualization environment, is also activated in the visualization environment to perceive the orientation of the scene and to understand the transformations (translation, rotation and zoom) that are operated on the entire 3D representation or on a particular object. Figure 7.5 illustrates the visualization environment after the user has imported the virtual 3D model and adjusted the size of the 3D axes.

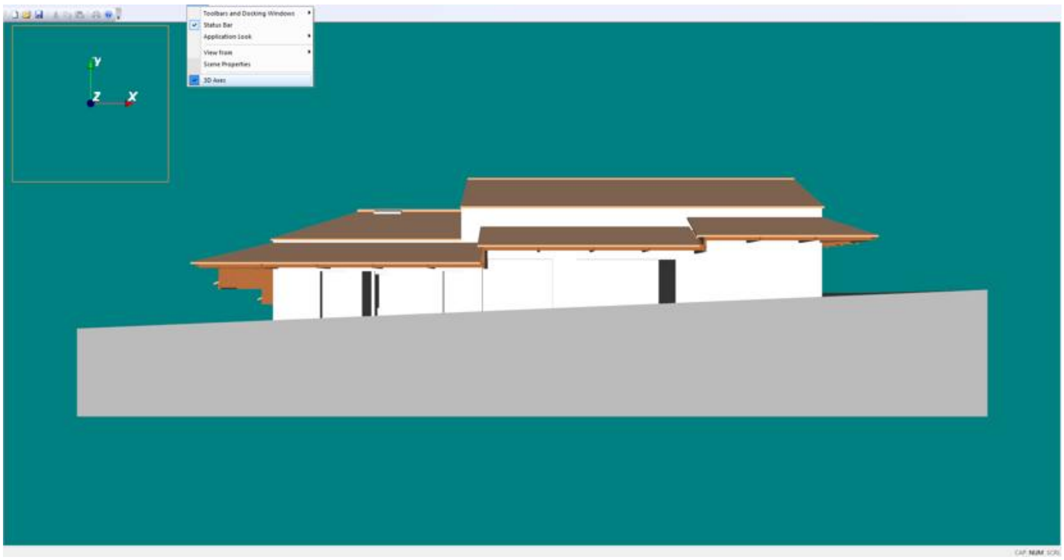


Figure 7.5: The virtual 3D representation of the *domus* of Carvalheiras

The cross-section tool was carefully explained to the archaeologists. It is composed of a plane, that defines the cutting plane, and of a normal vector that indicates the direction where the cut will be operated on the object. This tool creates a bounding box around the 3D model and positions a cutting plane parallel to the YOZ plane in the middle of the model. Associated to the plane there is a normal vector that indicates the cutting direction. Both plane and normal vector, are controlled by the mouse simultaneously and ensure a free positioning on the 3D representation of the archaeological element. Particularly, the selection and manipulation of this vector allow the arbitrary rotation of the cutting plane around the 3D model and the change in the direction of observation. At the same time, in the same window, a second renderer is created to display the cross-section result. Figure 7.6 shows the result of this operation.

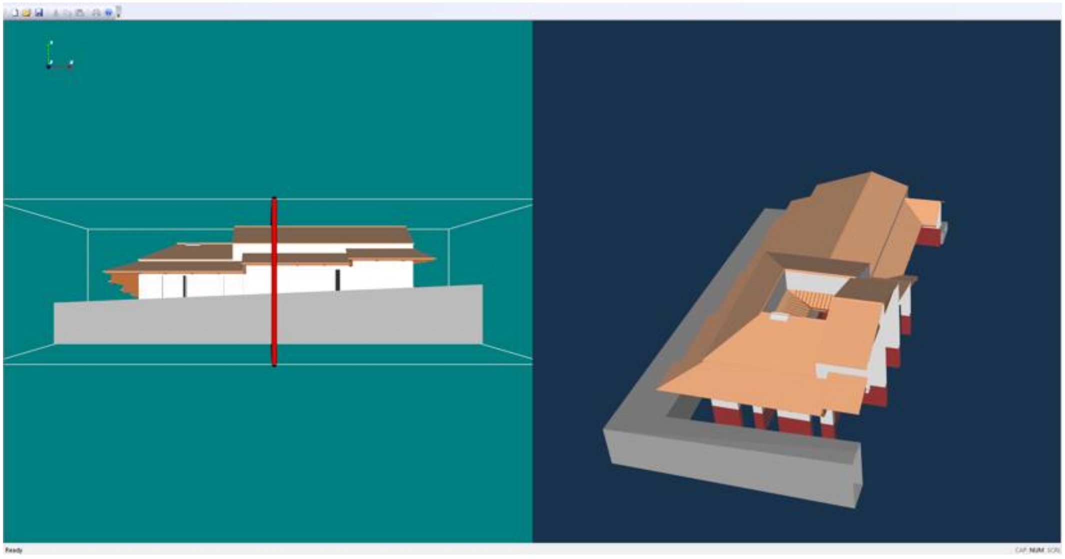


Figure 7.6: Initial position of the cutting plane (parallel to the YOZ plane)

7.1.4 Evaluation

The evaluation of the first prototype was focused on two tasks to increase the perception and insight of an archaeological element. On the one hand, the first task consisted in carrying out the observation and general analysis of the archaeological site on its 3D representation. The archaeologists had to perform the necessary actions to identify the various rooms and open spaces of the house, as well to observe construction details. On the other hand, the second task was to make arbitrary sections of the whole or of selected parts of the virtual model, to complement the general observation and analysis. In this task, the experts had to evaluate the easiness and quickness in which it is possible to define sections of the 3D model.

General observation and analysis

The archaeologists used the camera mode and trackball style interaction on the initial approach to perform this proposed task. Both preferred the trackball style because it represents the intuitive grab and move style and in this way, the expert could freely move around the 3D representation. By performing simple translation operation and rotations around different axes the archaeologist chose distinct viewpoints to understand the volumetry of the virtual representation, as pointed out in figure 7.7.

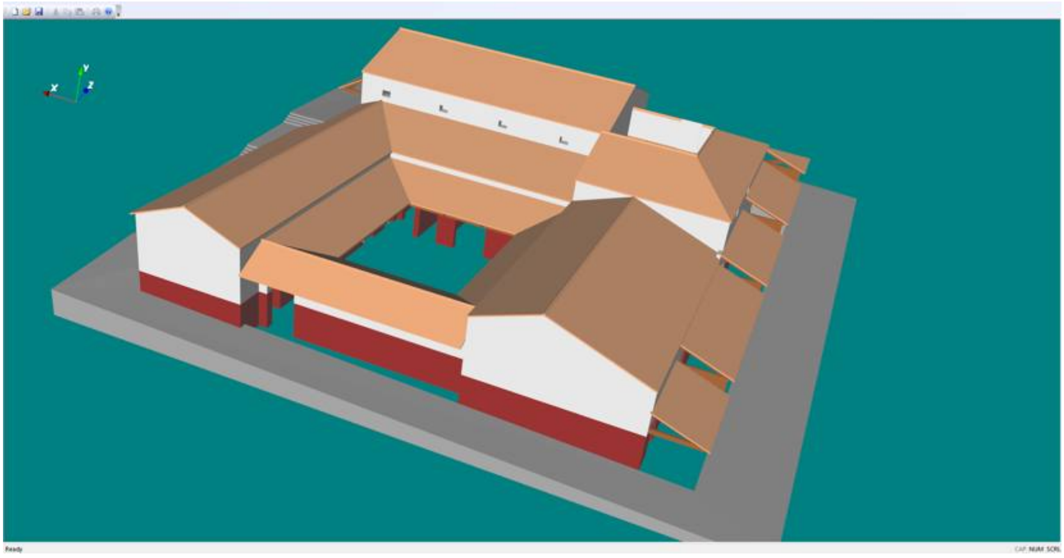


Figure 7.7: Adjusting the viewpoint

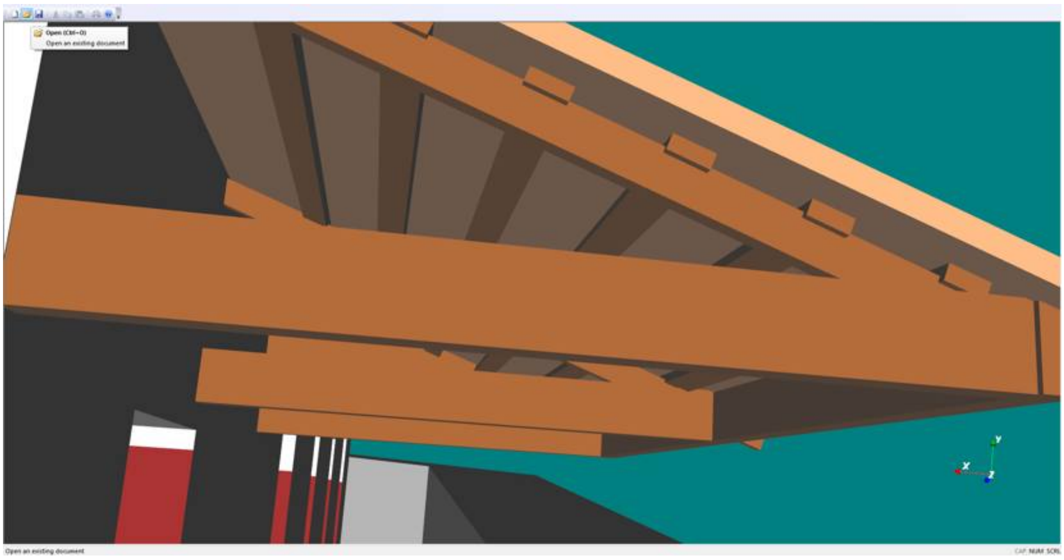


Figure 7.8: Zoom-in on the 3D model

The two experts used the features associated with the first level of the visualization model to perform the proposed task. However, the archaeologist A stated that to accomplish this task he did not have the necessity to use the dynamic scale feature because he had extremely well knowledge of the site.

To proceed with more detailed observation and analysis of the archaeological object, the experts approached the 3D model using a translation in the direction of observation (see figure 7.8). The zoom operation was performed with the mouse to closely perceive the different architectural elements that make up the virtual model.

The architectural elements were analysed with more attention after changing the interaction to the object mode and by selecting the element to be examined. While in the object mode, the transformation operations (3D translation, 3D rotation and zoom) were only applied to the selected object (see figure 7.9). In this way, the archaeologists were able to observe the interior of the *domus* of Carvalheiras and performs the deconstruction of the archaeological site.

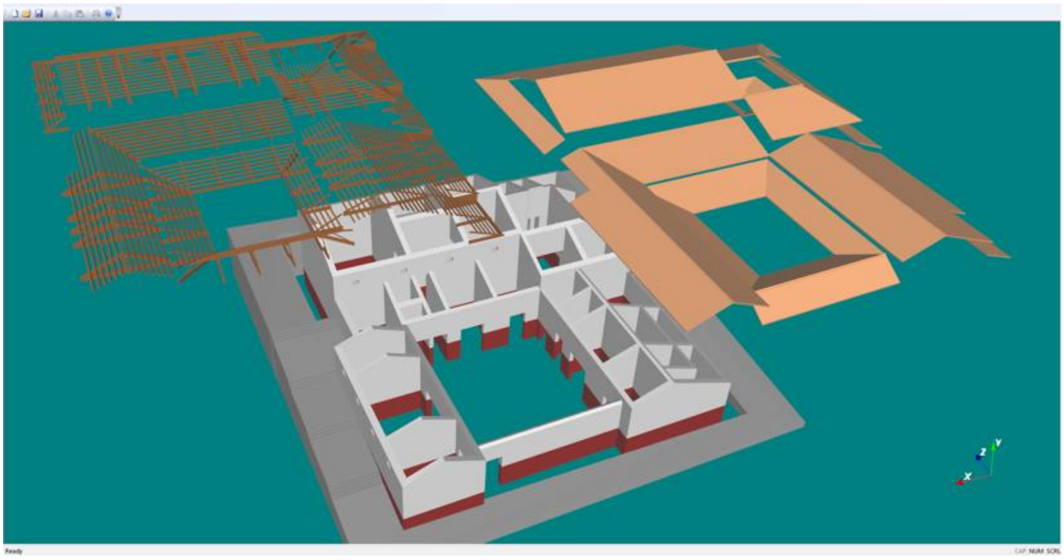


Figure 7.9: Deconstruction of the *domus* of Carvalheiras

Arbitrary sections

Once completed the first task, the archaeologists were asked to use the interactive cross-section method to create arbitrary sections on the virtual model. The aim of this task was to assess the usability of this tool and the improvement regarding the understanding of the archaeological element.

By rotating the cross-section plane 180° around the Z-axis (see figure 7.10) the users were able to examine the complementary 3D model to the object that is produced when the method is started. Figure 7.11 indicates a rotation of 90°, which placed the cutting plane parallel to the XOZ-plane. In this way, the archaeologists were able to analyze the plan of the *domus* in detail and, moving the cutting plane along the direction of its normal vector, each one observed the evolution in height of the structures of the building.

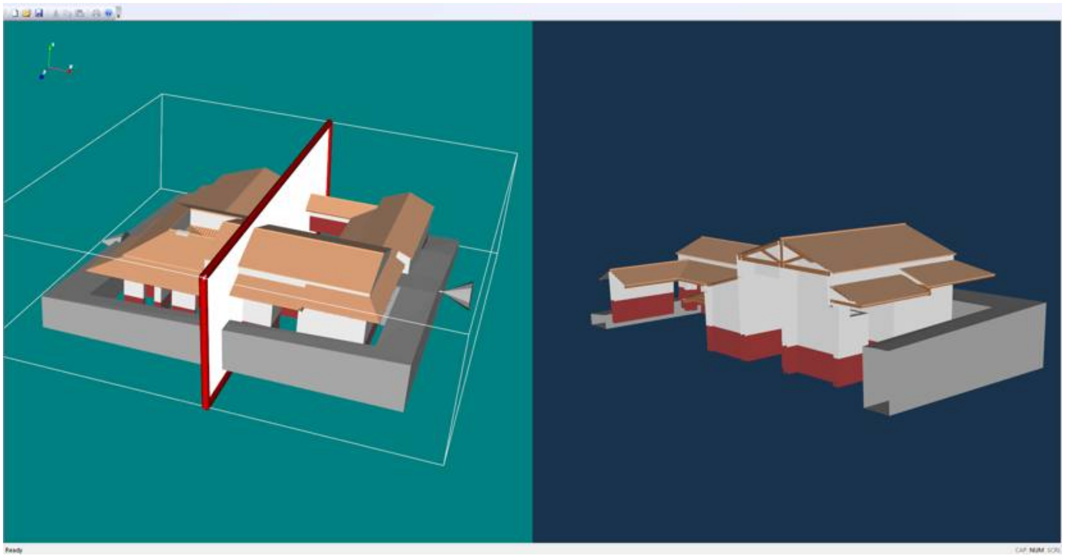


Figure 7.10: 180° rotation around the Z Axis (parallel to the YOZ plane)

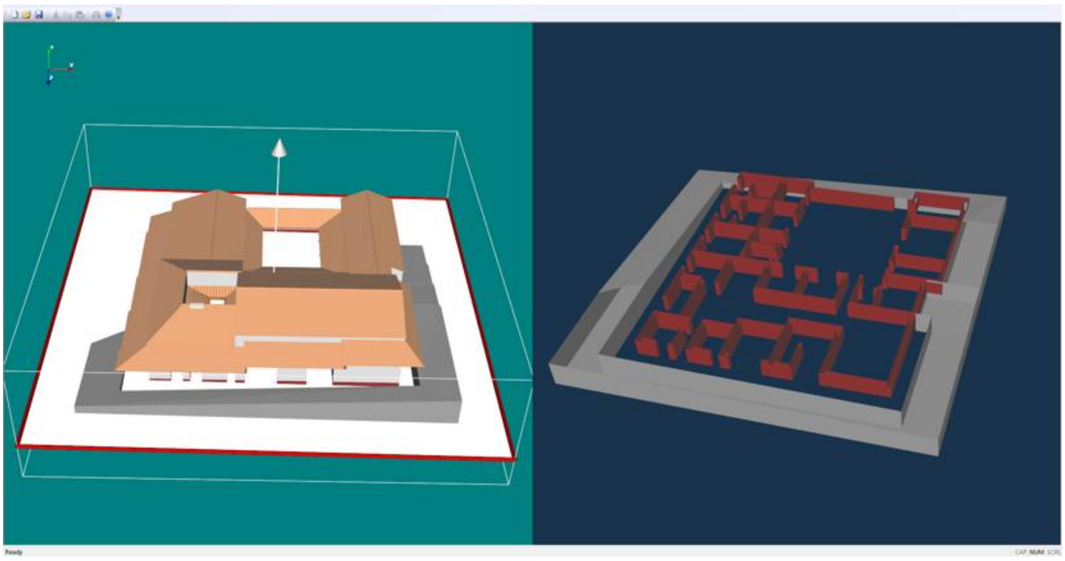


Figure 7.11: 90° rotation around the Z Axis and translation along the Y Axis

In addition to the cutting planes parallel and perpendicular to the faces of the bounding box, the archaeologists were able to define unlimited oblique cutting planes, as shown in figure 7.12. This facility allowed the archaeologists to chose the suitable plans for the analysis with considerable autonomy and ensured greater freedom while interpreting the virtual representation of the *domus*. This skill was also applied to particular objects of the *domus*, as can be observed in figure 7.13.

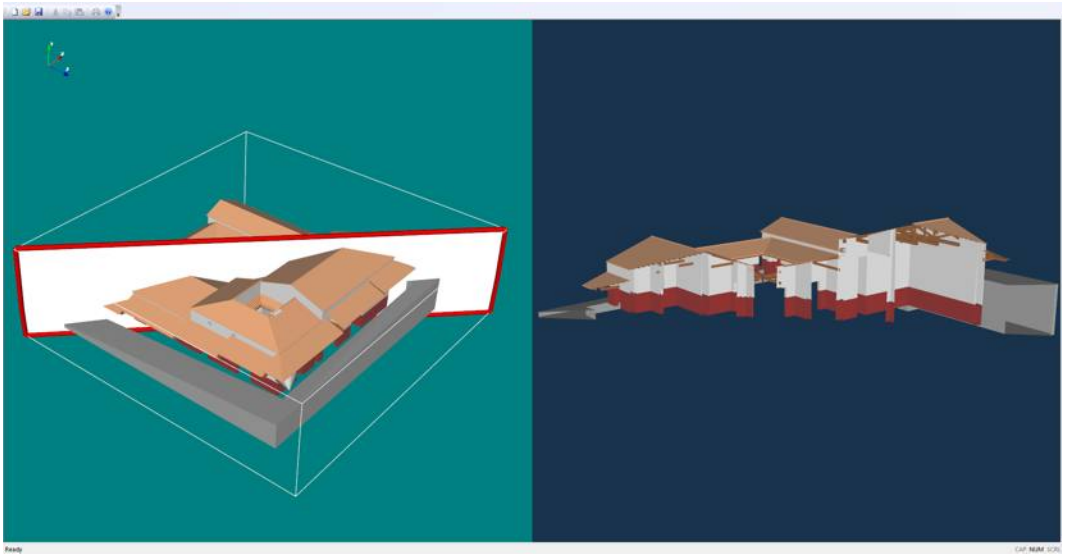


Figure 7.12: Arbitrary plane rotation around the Y Axis

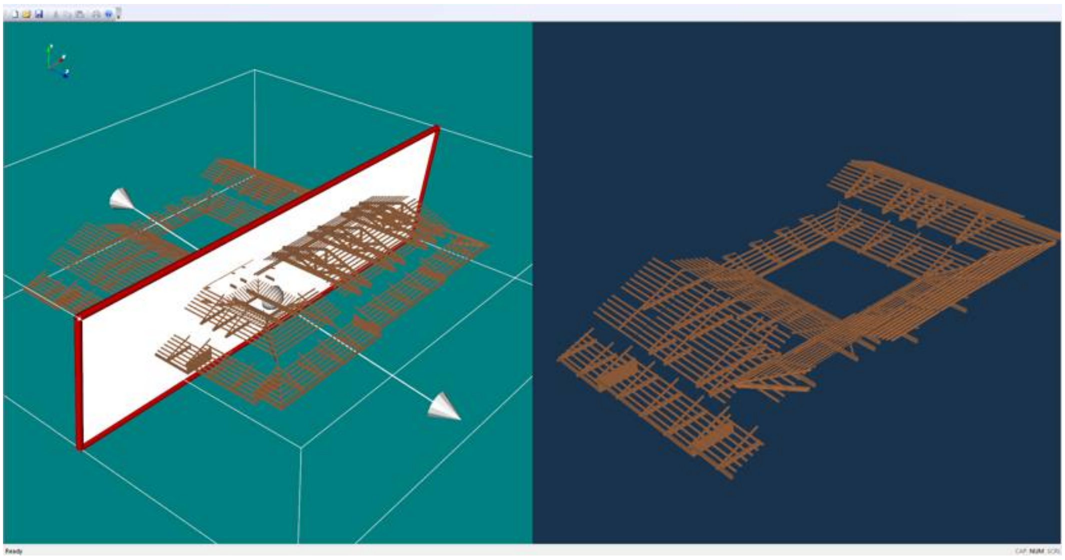


Figure 7.13: Cutting feature performed on the roof structure

7.1.5 Concluding remarks

The archaeologists were able to quickly understand the procedures for interacting with the 3D model and completed the proposed tasks without difficulty. Both were more comfortable with the trackball type interaction, although archaeologist B used the joystick type interaction during the initial phase. However, both agree that trackball type interaction is similar to the interaction they are used to when working with their usual *CAD* and *GIS* tools. Regarding the interaction mode, both users were familiarized with them and had no difficulty to chose the most adequate to perform the suggested tasks. The object mode was only employed to disassemble the 3D model. Table 7.1 illustrates the complete evaluation regarding the interaction with the virtual model.

	Archaeologist A	**Archaeologist B**
Joystick style	-	+/-
Trackball style	+	+
Camera mode	+	+
Object mode	+	+

Table 7.1: User-interaction evaluation of the first prototype

The first task was accomplished by combining the interactive scale model strategy with the computer graphics rendering strategy. In fact, while the general analysis was more based on the computer graphics rendering strategy, the deconstruction of the virtual model was centred on the interactive scale model strategy. The arbitrary sections task was resolved by joining the computer graphics rendering strategy with the semantically supplemented 3D representation. The interactive scale model did not play a significant role in the second task. All visualization methods associated with this prototype were used, although the dynamic scale procedure was only used by archaeologist B. Table 7.2 shows the relationship between visualization strategies, the visualization methods and the performed tasks.

The archaeologists used the features associated with the first level of the visualization model, although archaeologist A stated that to accomplish the proposed tasks he did not have the necessity to use the dynamic scale feature. The virtual model of the *domus* of Carvalheiras behaved like a mockup which the archaeologists had manipulated spontaneously, including removing and replacing some of its architectonic elements. The cross-section capability produced new arbitrary cuts of the *domus* which enhanced its readability and created new perspectives of the site.

	Task1	**Task 2**
Orientation	+	+
Dynamic scale	+/-	-
Interactive cross-section	-	+
Interactive scale models	+	+/-
Computer Graphics rendering	+	+
Semantically supplemented 2D and 3D representations	-	+

Table 7.2: Visualization methods and strategies of the first prototype used to perform the proposed tasks

It was possible to freely deconstruct the virtual model of the *domus* of the Carvalheiras and to create new readings about the site which influence the interpretation and the construction of new cognitive models associated with it. The various procedures were relevant for the analysis and to increase the understanding of the *domus* of Carvalheiras.

7.2 The second prototype

The purpose of this second prototype is to increase the understanding and insight of an archaeological element by analysing its 3D surface mesh. The 3D meshes used in this evaluation were produced with stereo-photogrammetry methods applied to digital images.

This prototype was assessed by two archaeologists with more than 10 years of field experience. The first archaeologist (Archaeologist C) had profound knowledge about the sites related to the *Bracara Augusta* project, while the second archaeologist (Archaeologist D) is associated to the *PoPaTerva* project. Both have considerable experience in using *CAD* and *GIS* software.

7.2.1 Sites used for evaluating the prototype

The current prototype has several features that may have greater applicability to specific archaeological elements. Thus, obtaining an excavation plan or user-assisted segmentation will make more sense in the context of an archaeological site, while the use of oblique lighting is more closely related to the analysis of rock art elements. Therefore, the archaeological data used for evaluation purposes are from the *thermae* of Alto da Cividade, the Fonte do Ídolo and the rock art elements in Souto Escuro 1.

The *thermae* of Alto da Cividade (Braga, Portugal)

The Roman public bath of Alto da Cividade is an important example of public equipment of *Bracara Augusta* that is well known and has been thoroughly interpreted over the last decades [139]. This Roman construction was identified in 1977 during excavations realized to confirm information related to the presence of roman architectonic material in the Alto da Cividade hill, in Braga (Portugal) (see figure 7.14).

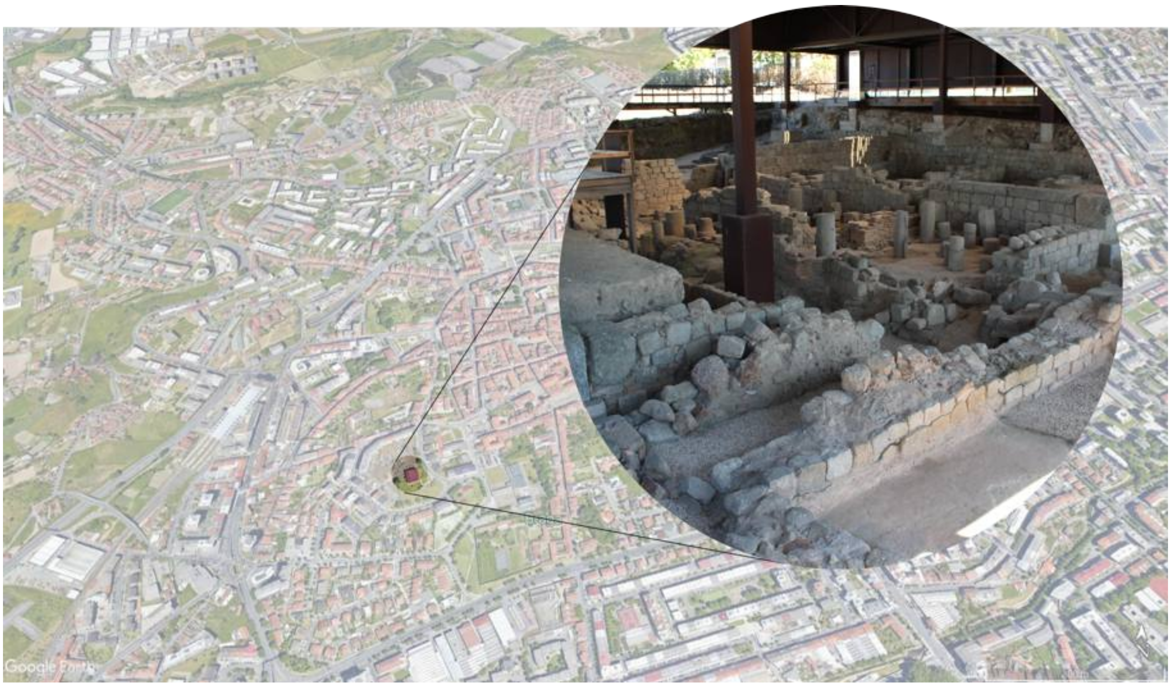


Figure 7.14: The ruins of the *thermae* of Alto da Cividade, in Braga (Portugal)

The first phase of archaeological excavations enabled to identify the northern and eastern limits of the building. Later, in the early 90's, the excavations were retaken and finally concluded in 1999. The archaeological research of these *thermae* enables, on the one hand, the understanding of the urban evolution in a highly important and noble sector of the Roman city, near the religious and administrative forum. On the other hand, it is possible to observe the architectonic changes in the architecture and the progress of materials used in this kind of leisure facilities. The complete and rigorous analysis of this Roman public building can be deepened in [140].

The Fonte do Ídolo (Braga, Portugal)

The Fonte do Ídolo is an emblematical Roman monument located outside the urban perimeter and, therefore, distant from the centre of the ancient Roman city of *Bracara Augusta* but in the centre of the modern Braga (see figure 7.15) [141]. This monument was discovered by the end of the 17th century and has been interpreted as a shrine dedicated to the worship of water and, for that reason, of great research interest since then.

Figure 7.15: The ruins of the The Fonte do Ídolo, in Braga (Portugal)

The architectonic structure was built on a granite outcrop that supports various inscriptions and figurative reliefs and since the beginning of the 20th century, it is classified as a Portuguese National Monument, due to its uniqueness. Nevertheless, only the excavations carried out between 2002 and 2003 enabled a new evaluation of the monument and the archaeological data recorded during this period enriched the archaeological interpretation of the site, contributing to strengthening the monuments singularity in the Iberian Peninsula. More thorough and comprehensive information about this Roman monument can be found in [142].

The rock art in Souto Escuro 1 (Boticas, Portugal)

The archaeological site of Souto Escuro 1 is implanted in the Terva Valley Archaeological Park, near the village of Bobadela (Boticas), at the western end of the *Leiranco* slope, which can be reached by the municipal road 527, in the *Boticas-Bobadela* direction (see figure 7.16).

Figure 7.16: The Rock art in Souto Escuro 1, Boticas (Portugal)

This site contains 6 groups of rock engravings, dating from the Iron Age and engraved on a partially fractured 14 m^2 granite slab facing the East to the Valley. On the surface of the slab, it is possible to observe sets of inscriptions, delimited by well-delineated grooves that develop from a central point to the outside, concentrically and pseudo-concentrically, conjugated with dimples, repeating circular, curvilinear and rectilinear motifs (the latter, a lesser amount).

These engravings belong to the so-called Atlantic art [143], which defines a stylistic set specific of the Peninsular Northwest and of the British Islands. It is not yet possible to verify whether the topography of the slab is natural or whether it was also shaped by who produced the pictures. However, it is clear that the choice of the area where the motifs were created is directly related to the topology of the granite base. The complete information about the site can be found in [144].

7.2.2 Virtual representation of the sites

The 3D reconstruction of the three archaeological elements was performed using the image-based data acquisition pipeline illustrated in figure 5.11. The photographic survey was completed by the author, with diverse cameras and at different times. Also, the reconstruction procedure was accomplished using varied software.

The *thermae* of Alto da Cividade

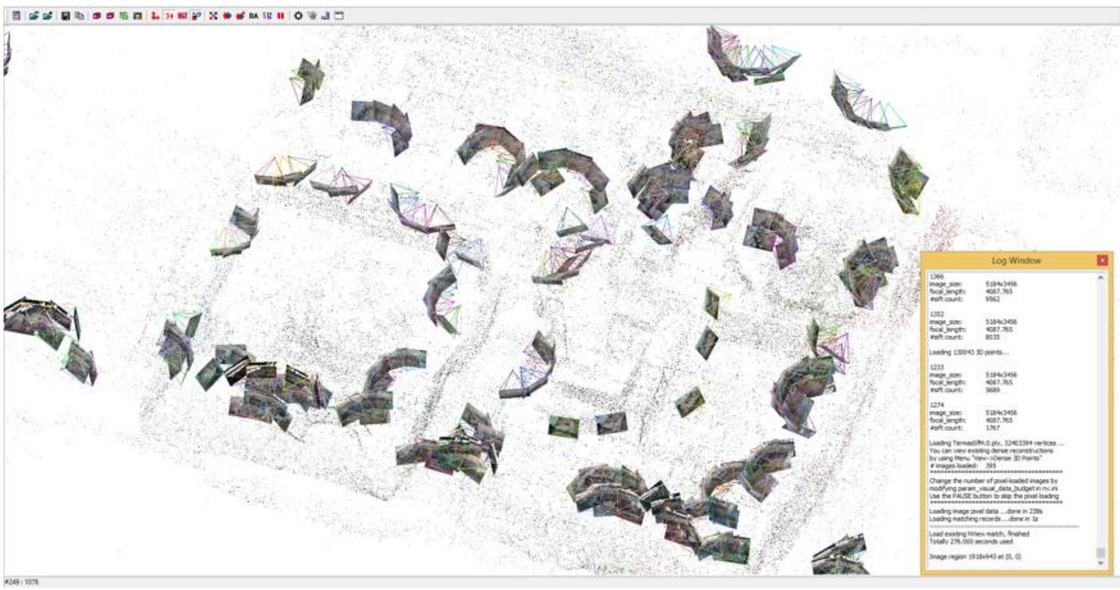


Figure 7.17: Sparse 3D point cloud generated with *VisualSfM*

The virtual restitution of the *thermae of Alto da Cividade* uses 395 images acquired with a *Canon 550D* camera. All photos were taken without flash and the focal distance of the lens was set to $18mm$. Each image is 5184 pixels wide by 3456 pixels high, with a resolution of 72 *ppi* (pixels per inch) and has been archived in *jpeg* format. There was no need to use physical targets as ground points since the site has noteworthy features on its surface that were suitable to be used as references.

These photos were imported into *VisualSfM* and processed to produce, first, a sparse 3D point cloud. Figure 7.17 shows not only this sparse point cloud but also the position where each picture was taken. If the point cloud is homogeneous, it is possible to assess that the image coverage of the object of interest is satisfactory.

The subsequent phase, which consists in the production of a dense 3D point cloud, generated a point cloud with 32.403.394 3D points that will be the input data for the 3D surface reconstruction (see figure 7.18). The surface reconstruction was performed using the *Poisson* filter implemented in *Meshlab 2016.12* and the texturing was also achieved with this open-source system using the initial set of photos. The resulting model was exported to an *Alias Wavefront Object* (*.obj*) and the texture to a corresponding *jpeg* file. The number of faces is 1.192.222, which is reduced by 22% using the NSA procedure.

Figure 7.18: Dense 3D point cloud generated with *VisualSfM*

The Fonte do Ídolo

The 3D reconstruction procedure of the Fonte do Ídolo was similar to the process carried out for the *thermae* of Alto da Cividade. A total of 121 images were acquired with the *Canon 550D* camera. The properties of the images are also identical to the images of the *thermae* of Alto da Cividade. As in the previous site, the stony surface of the façade has notable features that were used as control points. These images produced a dense point cloud with 11.638.656 points, that was transformed into a surface of 775.910 faces and simplified with the NSA algorithm by 20%.

The rock art in Souto Escuro 1

The data acquisition of the Souto Escuro 1 rock was performed using a *DJI Phantom 3 Pro* UAV with a *DJI-FC300X* camera which flew at an average speed of $3m/s$ and an approximate height of $5m$ from the ground. For scaling and georeferencing purposes, 5 ground control points were used. These control points were distributed in the middle (1 target) and at the outer limit (4 targets) of the site. Each of the 100 photos is 4.000 pixels wide by 3.000 pixels high, with a resolution of 72 *ppi*. The images were imported into *PhotoScan 1.4.5* from *Agisoft* and processed acording to the software's pipeline. The resulting dense point cloud was composed of 13.692.106 points and the 3D mesh had 2.738.358 faces.

Summary

	Thermae	**Fonte do Ídolo**	**Souto Escuro 1**
Camera	Canon 550D	Canon 550D	DJI-FC300X
Total images	395	121	100
File format	*jpg*	*jpg*	*jpg*
Pixels per inch	72	72	72
Image resolution	5184 x 3456	5184 x 3456	4000 x 3000
Dense point cloud	32.403.394	11.638.656	13.692.106
3D mesh faces	1.192.222	775.910	2.738.358
Reconstruction SW	VisualSfM+MeshLab	VisualSfM+MeshLab	PhotoScan

Table 7.3: Features of the image-based 3D surfaces

Table 7.3 shows the characteristics of the 3 models regarding mesh and point-cloud density, the features of the images and the cameras used for these surveys. It is interesting to note that while the survey performed with the *DJI* camera is less expressive with respect to the number of photographs and their resolution, the number of mesh faces is substantially higher. This is mainly due to the extremely homogeneous photographic coverage that can be obtained using the *UAV*.

7.2.3 3D interaction

The basic operations of interaction with the 3D environment were explained to archaeologists. The two types of interaction (*Joystick* and *Trackball*) were exemplified, as well as the *camera* and *object* modes.

All the visualization procedures associated with the second prototype were carefully explained to the users:

- *Dynamic scale* procedure — the tool has a graphical scale which can be complemented with four axes (left, right, bottom and top) that surround the visualization environment and indicate the scale of what is being observed. Each of these axes can be switched *on* or *off*, according to the user's preference. Also, the axes can be parametrized to display either distance values or the $X - Y$ coordinate values.

- *Colour elevation mapping* procedure — this tool has to be parametrized with regard to the colour range used to perform the mapping and the direction along which the colours are generated. By default, the colour range of the elevation filter is set to red $(1, 0, 0)$ and blue $(0, 0, 1)$, respectively the lower and upper elevation value, and the direction is perpendicular to the XOY plane. To improve the understanding of the colour mapping, it is possible to activate the *Scale Bar* option. By default, the number of labels of the scale bar is set to 2 and the scalar precision of the elevation values is set to 1.

- *Oblique lighting* procedure — this procedure starts after activating the virtual oblique lighting widget. This tool is represented as a sphere that enables the translational rotation around the object and the translation that moves away or approaches the light source from the object. The tool is operated only with the left mouse button. The lighting widget has to be set up regarding the lighting cone and the colour of the light. By default, lighting cone is set to 60° , the colour of the light is white and the intensity is set to 100%.

- *Interpretation-free alignment* procedure — as mentioned in the previous chapter, this procedure is based on the silhouette visualization methodology. It needs to be set up regarding the viewing direction, the minimal angle to detect sharp edges (feature edges), the colour property of the extracted edges and the line width of the edges.

- *User-assisted segmentation* procedure — the first step of this tool is to switch to the mouse-based selection style to position the points that clearly define the limit of the region to be extracted. The creation of the regions is very intuitive, by clicking with the left mouse button on the place of the surface that is part of the boundary of the region to be extracted. The next step activates the filter that performs the segmentation of the region, based on the previously generated list of points that define the limit of the region of interest.

7.2.4 Evaluation

The purpose of the image-based 3D representation of archaeological elements is to improve the archaeological record that traditionally was mostly supported by 2D entities. This realistic representation of the archaeological elements represents non-segmented data that has to be thoroughly analysed before performing any classification.

Unlike what happened in the first prototype, the visualization methodologies of this prototype intend to assist the archaeology team in the classification of the surveyed and recorded data. The classification process is particularly demanding and challenging responsibility, therefore the visualization methods must be sufficiently reliable.

To assess the usefulness of each method, relevant analysis tasks were defined, which were performed on the 3D models. Each task is intended to increase awareness and knowledge of the archaeological element that has been processed. Thus, to evaluate this prototype, the following tasks were suggested:

- *Global Perception enhancement and analysis* — Analyze the site in order to increase the perception of the various spaces/areas and to find any relations between them;

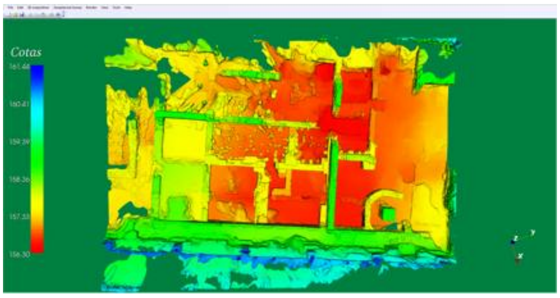
- *Interpretation-free plan of the site* — Create a site plan, free from any human interpretation and that can serve as a starting point for archaeological analysis;

- *User-assisted segmentation* — Highlight and separate from the original surface of the archaeological element two regions that represent segments with potential interest for later analysis;
- *Perception enhancement using oblique lighting* — Carry out an analysis on the virtual 3D surface of the archaeological element and undoubtedly identify and highlight eventual existing engravings.

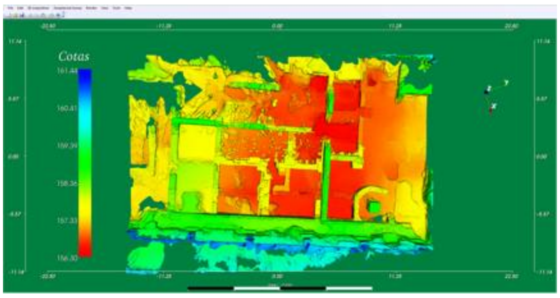
Global perception enhancement and analysis

The virtual 3D model of the thermae of Alto da Cividade was used to complete this first task. After importing the virtual model into the virtual visualization environment, the archaeologists observed the existence of several spaces separated by vertical structures, but both noted lack of information regarding the scale of the observed space and both recognized the difficulty to understand the dimensions of the virtual restitution. To improve the understanding of the model regarding its dimensions, both users activated the graphical scale in the visualization environment.

(a) Interactive distance scale



(b) Color elevation map with scalar bar



(c) Color elevation map with scalar bar and dynamic scale

Figure 7.19: Global perception enhancement and analysis

The archaeologists parametrized the graphical scale tool with the four axes and correspondingly used the distance scale mode to understand the dimensions of the 3D representation of the *thermae*. Although it was not possible with this tool to determine the exact measurements of the structure, the archaeologists were able to have a fairly rough idea of its width and length: while interacting with the virtual model and displaying it on the rendering window, as can be seen in figure 7.19a, both recognized that the displayed graphical scale represented approximately 17m in the real world.

The global perception of the archaeological element was considered, by both experts, acceptable. They also agreed that the result represented an improvement, but the understanding of the site in terms of altimetry was unsatisfactory. For this reason, the archaeologists decided to apply the colour elevation mapping procedure to the virtual model, in order to assess the altimetry variation of the current archaeological site. It was important for both users to activate the Scale Bar option and after some testing, they chose to display 6 labels (see figure 7.19b) and to set the precision to 2 (centimetre precision). Both archaeologists realized that combining the interactive distance scale procedure with the colour elevation mapping method would improve the perception of the site (see figure 7.19c).

The archaeologists completed successfully the proposed task and did not find any difficulties in interacting with the initial model, nor parameterizing the elevation colour mapping filter. The two experts were able to:

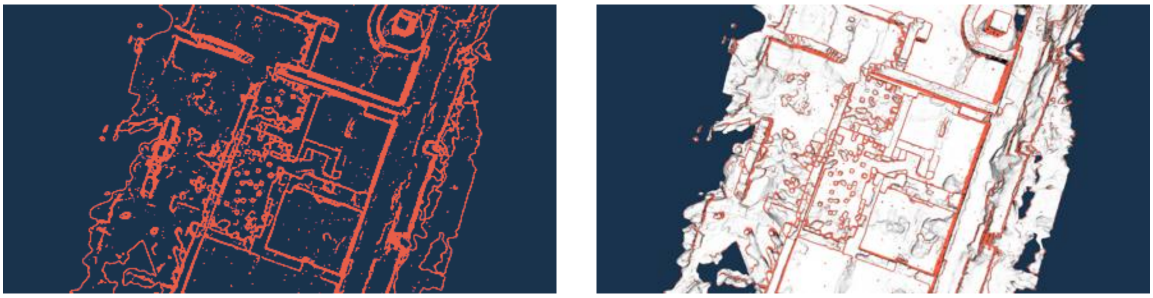
- identify the areas of the site that are approximately at a similar elevation;
- recognise the square tiles as the *pilae* used in the underfloor heating system (*hypocaust*) of Roman baths;
- distinguish a circular structure that might define a reservoir;
- distinguish the walls of some compartments of this Roman bath.

Interpretation-free plan of the site

The second task suggested to create an uninterpreted plan of the archaeological site, that might be used for archaeological analysis and interpretation purpose. This task complements the previous and, therefore, it was also performed on the 3D model of the *thermae* of Alto da Cividade.

The first expert performed this assignment assuming the default value of the viewing direction, which was the direction from the viewpoint of the active camera of the renderer to the centre of the object. The minimal angle to detect feature edges was set to 60°. The colour of the edges and the line width was set freely by the user.

The graphical result, after applying this visualization method to the virtual model of the *thermae*, is a non-realistic representation of the archaeological data (see figure 7.20a). The alignment of walls, the *pilae* and the circular structure were clearly identified. However, there remained also some undistinguishable elements. These elements were not categorized and, therefore, the archaeologist chose to superimpose the non-realistic line model over the initial model (see figure 7.20b) to evaluate if the overall perception of the representation could be enhanced. The expert recognized that some interior loops in the plan were due to inaccuracy of the mesh and did not have any archaeological relevance.

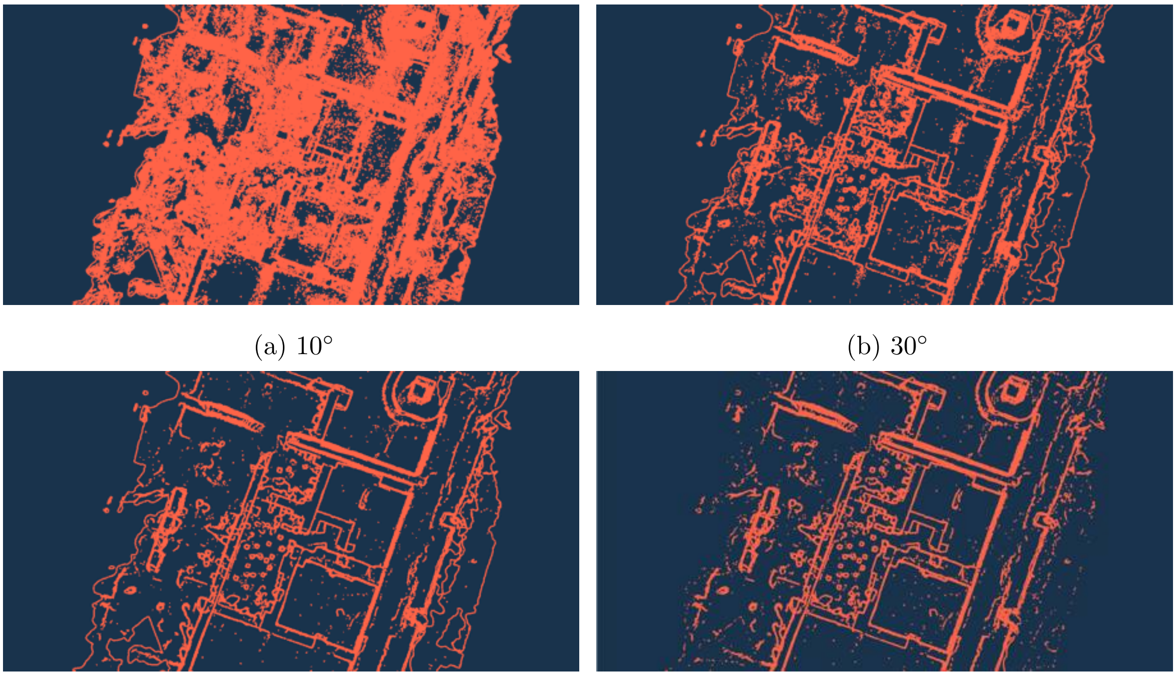


(a) Simple procedure (b) With superimposition

Figure 7.20: Interpretation-free plan of the *thermae*

After this procedure, the user was able to value what was important for archaeological purposes and what in his opinion should be considered undesirable noise. The archaeologist stated that the resulting non-realistic 3D model could be considered an interpretation-free plan of the site and could serve as an initial basis to analyse the space. However, he stressed out that the resulting plan might be a reasonable starting point, but it is not the final excavation plan.

The second archaeologist began the execution of the proposed task maintaining the default viewing direction but successively varying the angle to detect feature edges. He noticed that in this specific case the higher the angle to detect the feature edge, the cleaner the uninterpreted plan of the *thermae*. Figure 7.21a was generated using an angle of 10° which produced an unclean and blurred 3D representation where it was difficult to recognize the alignments of the walls. The next example in figure 7.21b was produced using an angle of 30°: the 3D representation is cleaner and it was possible to recognize some alignments which represented existing structures. The example in the following figure 7.21c was produced with a feature edge angle of 60° and a considerable improvement of the 3D representation could be noticed. The user referred that the alignments of the walls were well defined and it was possible to recognize a consistent plan that could represent the site. The final example in figure 7.21d was created using an angle of 90°. The archaeologist noticed that the resulting representation was similar to the previous one. However, the outer contour of the model had disappeared. He referred that although the last two examples were very similar, it seemed that the last one had eliminated some lines that could have some significance for archaeological purposes.



(a) 10° (b) 30°

(c) 60° (d) 90°

Figure 7.21: Using different angles to detect feature edges

The proposed task was successfully concluded by both archaeologists. They did not reveal major difficulties in interacting with the 3D model nor parametrizing the feature edge extraction filter. Both recognized on the non-photorealistic representation of the site the distinct areas and remaining structures of the Roman bath.

User-assisted segmentation

In the third task, the archaeologists were suggested to select and extract from the original unsegmented surface two representative regions with potential interest for later analysis. For this task, the proposed archaeological 3D model was the Fonte do Ídolo. Both experts chose to interact with the model using the *trackball* type interaction and the *camera* mode.

The first archaeologist decided to extract from the original surface the *aedicule* (small shrine), because of its importance as a sculptural element of the site and the frontal façade of the rock that possibly supported a pilaster which flanked the figure dressed in a tunic, because of its convex shape. He started the shape extraction procedure by positioning the model properly and by switching the interaction style to the mouse-based selection style. The region that surrounded the *aedicula* was defined using 9 points and for the second region, the archaeologist used 14 points to ensure the preservation of the convex shape. Figure 7.22 illustrates the two segmentation areas defined by the archaeologist.

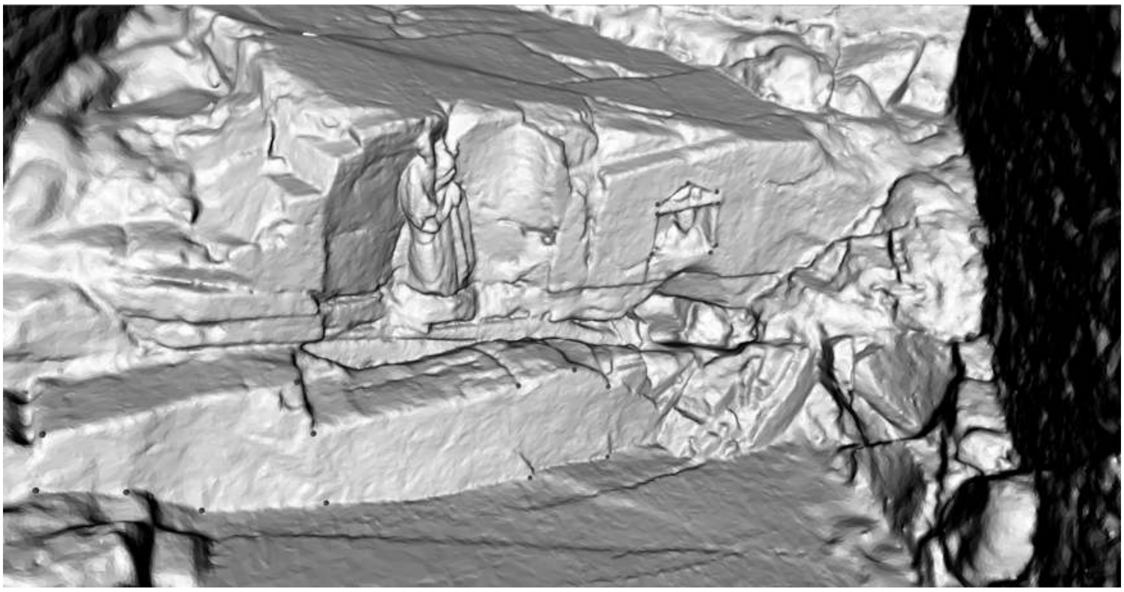


Figure 7.22: User-assisted delimitation of 2 segmentation areas

After defining the regions of interest, the next step was to activate the geometry extraction filter to separate the two regions from the original surface. The archaeologist chose to assign new colours to each new region, on the one hand, to assess whether it corresponds to the area which was initially defined, on the other hand, to highlight the new areas (see figure 7.23).

The last step of the proposed task was to analyse and manipulate the segmented new regions. The archaeologist performed this action by returning to the trackball interaction type and switching to the object interaction mode. Subsequently, he placed the cursor over the region of interest and used the mouse buttons to perform any translation, rotation or zoom operation (see figure 7.24).

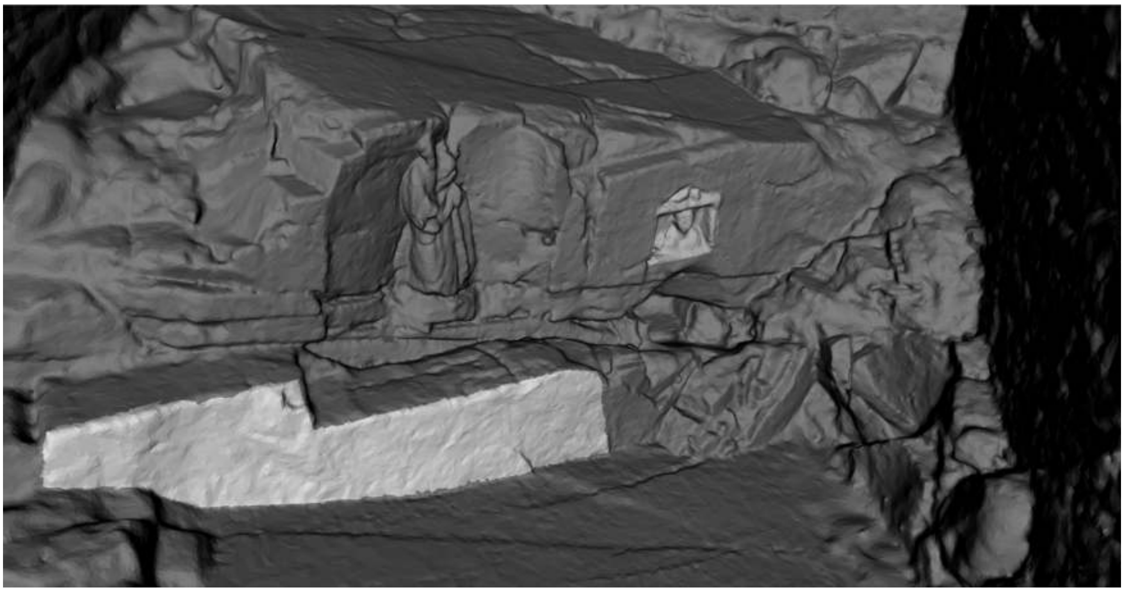


Figure 7.23: Segmentation of 2 predefined areas

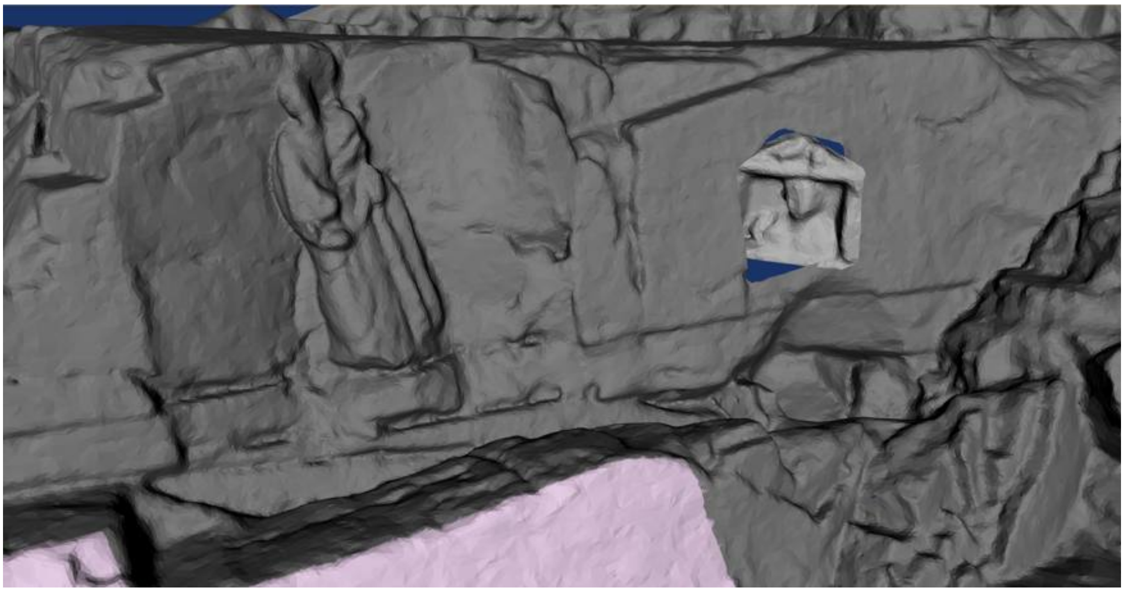
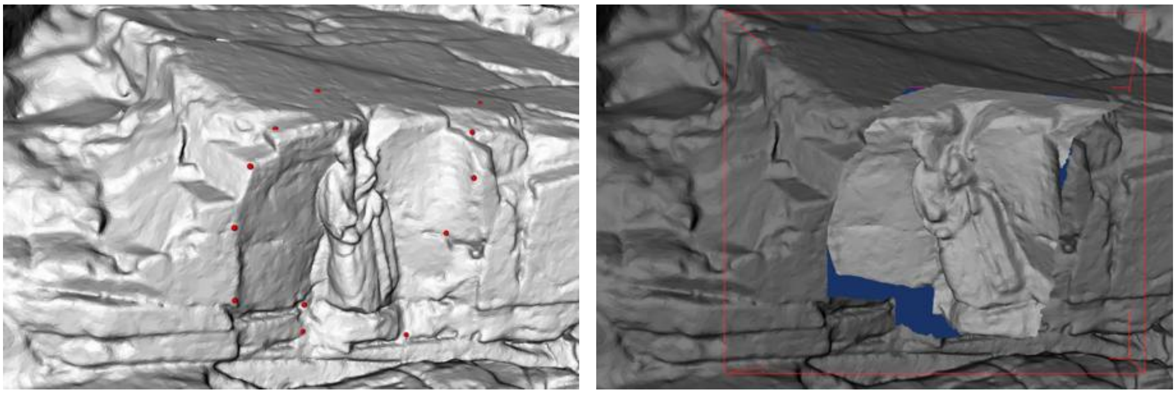


Figure 7.24: Interaction with one of the segmented areas

The second archaeologist chose the *aedicule* and the figure dressed in a tunic to execute the proposed task, because of the archaeological relevance of both sculptural elements. He positioned the model properly to perform the definition of the regions of interest. Each region was defined using 8 and 12 points, respectively. The following steps to extract the two shapes from the original surface were executed similarly to the first user. Figure 7.25 illustrates the delimitation of the region of interest (figure 7.25a) and the surface extraction (figure 7.25b) performed on the figure dressed in a tunic.



(a) Delimitation of the region of interest (b) Surface extraction

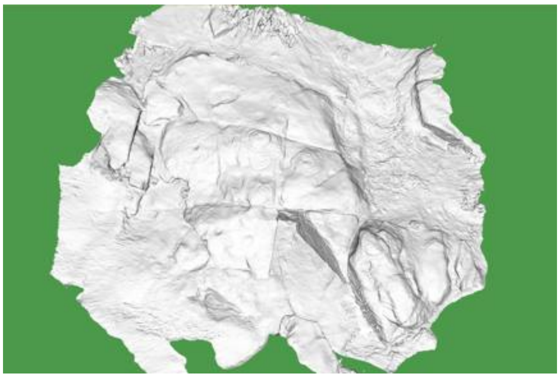
Figure 7.25: User-assisted segmentation of the figure dressed in a tunic

Both archaeologists concluded the task without difficulty, although the first had some trouble when switching from the trackball type interaction to the mouse-based selection style. The concern was that he did not immediately understand that, in order to reposition the 3D surface using the left mouse button, he had to change to the trackball type interaction. The second user was concerned with the fact that the limit of the region was visually illustrated only with highlighted points and not with a continuous line. However, the users agreed that:

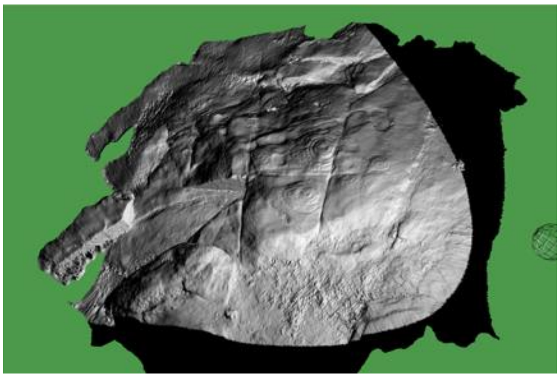
- it was intuitive to mark the points on the surface to define each region of interest;
- the resulting new surfaces corresponded to the marked region;
- it was intuitive to separate the new regions of interest and interact with them.

Perception enhancement using oblique lighting

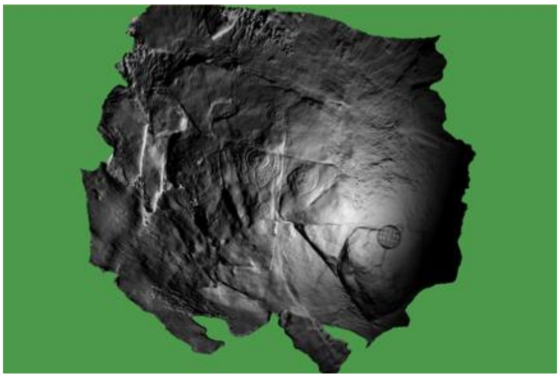
In rock art analysis, it is very common to use oblique lighting in the field, during the night, to enhance the perception of the engravings. The task proposed to the archaeologists was to carry out an analysis on the virtual 3D surface of the rock of Souto Escuro 1 and verify if they were able to undoubtedly identify and highlight all the existing engravings. Figure 7.26a illustrates the 3D representation of the Souto Escuro 1 rock after importing it into the visualization environment and without any external lighting.



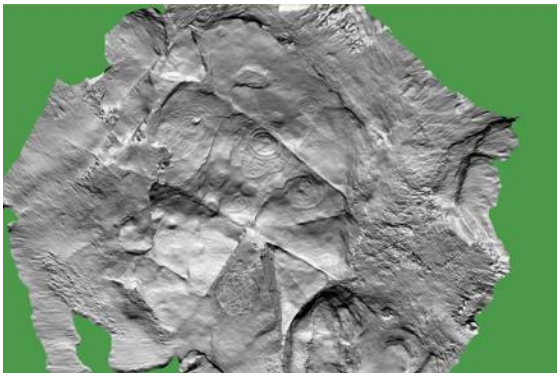
(a) Without oblique lighthing



(b) With oblique lighting – lighting cone set to 60°



(c) With oblique lighting – lighting cone set to 90°



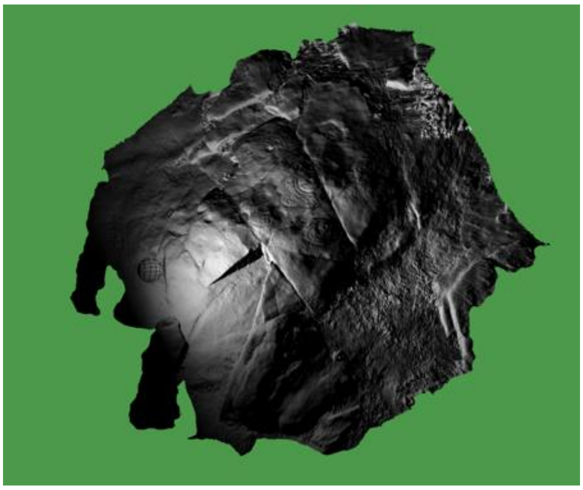
(d) With oblique lighting – point light

Figure 7.26: Virtual 3D surface reconstruction of the Souto Escuro 1 rock

The first archaeologist activated the virtual oblique lighting tool after loading the 3D representation of the Souto Escuro 1 rock into the visualization environment. He maintained the default setup and moved the virtual light around the 3D representation of the rock. Although he recognized the motives on the rock, he was not satisfied with the visual effect of this setup because everything outside the lighting cone was set without any illumination (see figure 7.26b). For the next setup, he maintained the light colour and the light intensity but changed the lighting cone to 90°. In his opinion, the visual understanding of the archaeological element improved and while moving around the object it was possible to identify the entire motives of the rock (see figure 7.26c). The last setup the archaeologist tried out was the point light setup with the default light colour and light intensity. He considered the visual results also very positive and recognised all the motives on the rock (see figure 7.26d).

(a) 50% intensity

(b) 75% intensity



(c) 100% intensity

Figure 7.27: Oblique lighting performed on the Souto Escuro 1 rock using different light intensities

The second expert behaved very similarly to the first and the results he obtained from performing the proposed task were also very similar. However, he also chose to vary the light intensity as shown in figure 7.27. The first example (figure 7.27a) represents oblique lighting set up with a 90° cone, white light and 50% light intensity. The archaeologist found it extremely difficult to identify the rock art motives using these settings because de archaeological object was too dark. Therefore, he changed the settings to 75% of light intensity, maintaining the other parameters and found that it was already possible to detect all rock motifs (figure 7.27b).

Both archaeologists concluded the proposed task without any difficulty and manipulated the 3D surface and the oblique lighting using the trackball interaction type. They also observed that the visual enhancement of the rock art motifs occurred when oblique lighting tool was set either with a 90° lighting cone of the spotlight or with a point light. The second expert noticed that setting the light intensity below 75% did not facilitate the understanding of the motifs.

7.2.5 Concluding remarks

Both archaeologists comprehended the available procedures of the second prototype and accomplished the proposed tasks without any major difficulty. Like the experts in the first prototype, both preferred the trackball type interaction wich they used mainly combined with the object interaction mode. The object mode was occasionally activated to separate the segmented objects from the original surface or to reposition the oblique lighting tool. Table 7.4 clarifies the evaluation regarding the interaction with the virtual model.

	Archaeologist C	**Archaeologist D**
Joystick style	-	-
Trackball style	+	+
Camera mode	+	+
Object mode	+/-	+/-

Table 7.4: User-interaction evaluation of the second prototype

The two tasks performed on the virtual representation of the *thermae* of Alto da Cividade contributed to the visual enhancement and understanding of the surveyed data. On the first task, this improvement resulted from the combination of different visualization methods such as the elevation colour maps, the scale bar and the graphical scales. The visual enrichment in the second task resulted from merging two distinct 3D representation models: the extracted feature edge model and the original 3D surface.

The result of the user-assisted segmentation on the Fonte do Ídolo representation was soundly adequate while using both convex and concave limits. The interaction with the extracted surfaces was performed flawlessly and the users identified the principal elements of the *aedicula* and of the figure dressed in a tunic. However, regarding the *aedicula*, it was not possible to recognize the epigraphic elements. Nevertheless, the archaeologists understood that this was not due to the visualization methods and could be solved in the future with a more careful data acquisition plan.

The archaeologists accomplished the last proposed task on the Souto Escuro 1 rock without major difficulties and considered the interaction with the oblique lighting tool not difficult. It effectively enhanced the perception of the motifs on the rock.

	Task1	**Task 2**	**Task 3**	**Task 4**
Orientation	+/-	+/-	+/-	+/-
Dynamic scale	+	+/-	+/-	+
Colour mapping	+	-	-	-
Virtual oblique lighting	-	-	-	+
Interpretation-free alignment	-	+	-	-
User-assisted mesh segmentation	-	-	+	-
Interactive cross-section	+/-	-	-	+/-
Interactive scale models	+	+/-	+	+
Computer Graphics rendering	+	+	+	+
Semantically supplemented 2D and 3D representations	+	+	-	-

Table 7.5: Visualization methods and strategies of the second prototype used to perform the proposed tasks

The *global perception enhancement and analysis* and the *interpretation-free plan of the site* were executed combining the interactive scale model strategy, the computer graphics rendering strategy and the semantically supplemented 2D (task 1) and 3D (task2) representations. The other two proposed tasks were implemented by joining the interactive scale model strategy with the computer graphics rendering strategy. The semantically supplemented 2D and 3D representation strategy was not used for these two tasks. All visualization methods associated with this prototype were used, however, the first archaeologist assumed mostly the default values of the procedures while the second one was more comfortable to change the different parameters of the applied 3D filters. The table 7.5 shows the relationship between visualization strategies, the visualization methods and the performed tasks.

7.3 The third prototype

The third prototype aims the successful handling of ERT-based 3D point clouds to understand the dataset which might relate to archaeological features. The evaluation of this prototype will be executed using the data from the ERT-survey performed at the Sapelos Hillfort (Boticas, Portugal).

This evaluation will be performed by two archaeologists. The first expert (Archaeologist E) has over 15 years of field experience and considerable familiarity with the geophysical survey in archaeology. He also knows the site extremely well. The second expert (Archaeologist F) has about 10 years of field experience, but limited knowledge about the geophysical survey. He also knows the site extremely well.

7.3.1 The Sapelos hillfort (Boticas, Portugal)

Figure 7.28: The Sapelos Hillfort, in Boticas (Portugal)

The Sapelos hillfort is located in the Terva Valley Archaeological Park, at an average height of 610 m, near the village of Sapelos (Boticas) and with an area of approximately 3 ha (see figure 7.28). This hillfort is one of the nine fortified settlements occupied during Iron Age in the upper Terva River valley and it is most certainly related to the exploitation of the metallic mineral resources available (gold and tin), which later were of considerable interest in the Roman period.

This hillfort strategically controls the entire valley from its southern limit, standing in a privileged position towards the natural crossing routes and the mineral cores. The hillforts' surface has micro-topographical aspects that induce the localization of buried structures and some remaining walls are partially visible amongst the vegetation cover. The settlement was extremely fortified with considerable defensive walls placed at two distinct levels around the hilltop and slopes. It also had a complex system of deep trenches, one surrounding the entire hill and seven other arranged in a deltoid figure towards the valley. For an exhaustive description of this archaeological site please refer to [145].

7.3.2 ERT-survey at the Sapelos hillfort

One of the main aspects focused on the *PoPaTerva* project is the application of remote sensing techniques to enhance non-visible archaeological features. The Terva valley has a very important lithological formation and particularly the Sapelos settlement stands over a levelled hilltop, crossed by quartz veins, following the general orientation of NNE-SSW, trending with the *Régua-Verin* tectonic fault [146]. Therefore, having in mind the geological context of the Sapelos hillfort, the first geophysical survey prepared was the ERT method.

Survey setup

The ERT survey was performed over a linear grid with X parallel offset distance of 4 m, crossed by a Y distal lines with 10 m spacing (see figure 7.29). The geophysical team used for this survey a *Syscal R1 plus* resistivity meter from *IRIS Instruments*, designed for medium-depth exploration, and a total of 72 electrodes for an inter-electrode linear spacing of 1 m.

The electrodes were connected using the *Wenner-Schlumberger* array configuration and the resistivity data inversions were processed with *RES2INV*® software, using the smoothness

-constrained least-square method, to build up the customary pseudo-sections (see figure 7.30). The inter-electrode setup started to return data at approximately 0,50 m depth below the current surface and the returned data had a resistivity class range between 146,03 Ω.m and 1.586.377,75 Ω.m [147].

Figure 7.29: Linear grid of the ERT survey

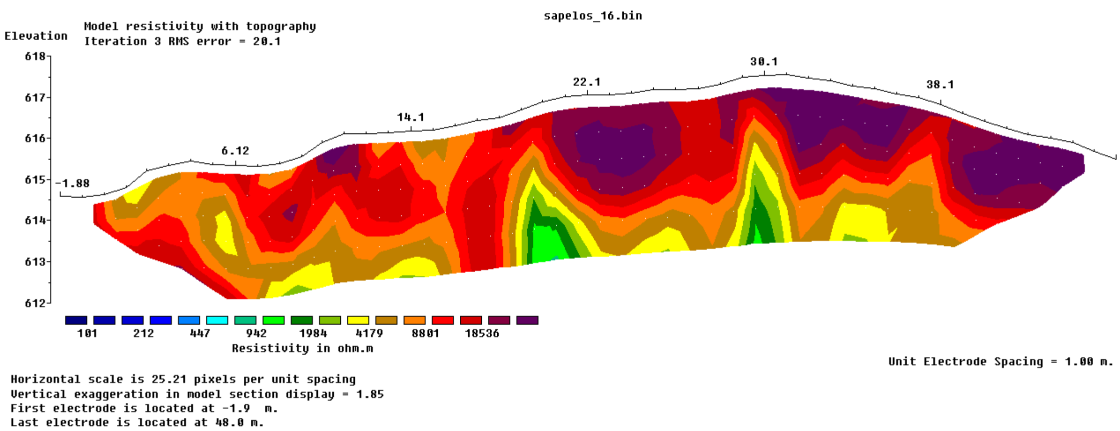


Figure 7.30: Inverse model pseudo-section of a profile surveyed at Sapelos Hillfort, modelled with topographical correction

4D data representation

A simple and efficient procedure for storing the information regarding the ERT survey is to use a multidimensional array data structure that is stored as a *CSV* file (*C*omma-*S*eparated *V*alue file format). Each line entry of the *CSV* file characterises a 4-tuple $(x,\ y,\ z,\ \Omega)$. The coordinates (x, y, z) represent a geo-referenced point in space where the measurement has been taken and Ω is the associated electrical resistivity value.

7.3.3 3D interaction

All the 3D interaction facilities are the same as from the previous prototypes and were demonstrated to te users. The visualization methods associated with this prototype were carefully explained to the archaeologists that have evaluated the prototype.

An important aspect is to define the range of interest that represents scalar values with potential archaeological significance. In this specific case, the range of resistivity values that may be of interest to archaeological research will be defined. By default, a colour table and an opacity table are associated with the model produced. Both colour and transparency are associated with resistivity values.

The archaeologists will also have the need to activate an implicit plane widget that will sweep through the volume representation to unveil what is in the interior of the volume. After activating the widget, the volume will be highlighted with a bounding box and the sweeping plane will be visible, as well as its normal vector.

7.3.4 Evaluation

As already mentioned before, the purpose of using geophysical survey, and particularly the ERT method, is to point out to geophysical anomalies that might relate to archaeological features, in a non-intrusive way. However, the model interpretation might not be simple for archaeologists that have not the necessary skills to understand the geophysical data through scalar models interpretation. The raw data and the visualization models are not understandable in a user-friendly way, so the archaeologist will most certainly face some difficulties to understand the data and its visual output. Therefore, an appropriate visual enhancement of the dataset is required to straightforwardly understand the results from the geophysical ERT survey.

To evaluate this prototype, the archaeologists were suggested to complete the following tasks:

- Generate a spatial representation of the recorded data;
- Create a volumetric representation of anomalies that may be related to archaeological features.

Spatial representation

The visual representation of the ERT data is illustrated in figure 7.31 and represents an unstructured point set grouped in a uniform point cloud but without any topological relation between them. However, the density of the grid does not provide useful information for the archaeologists, besides clarifying the inter-electrode space established during the survey.

The spatial representation will be a bounding volume that involves all the points obtained with the ERT survey. There are two possible approaches to perform the 3D representation of the bounding volume.

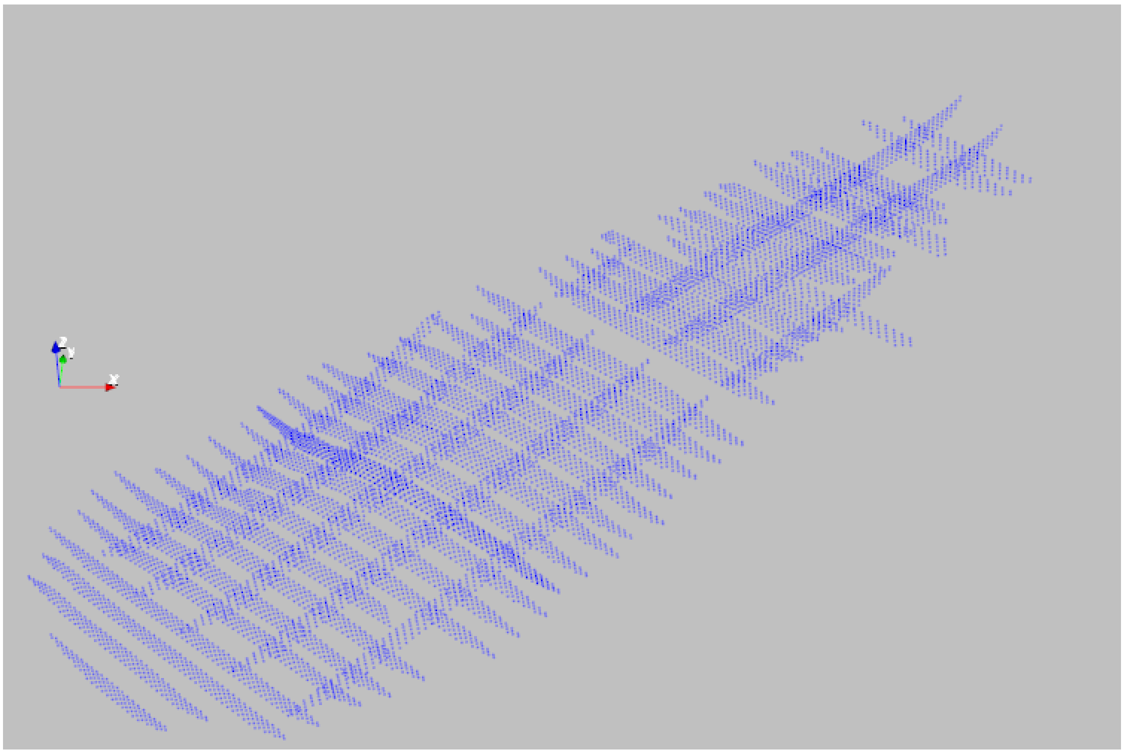
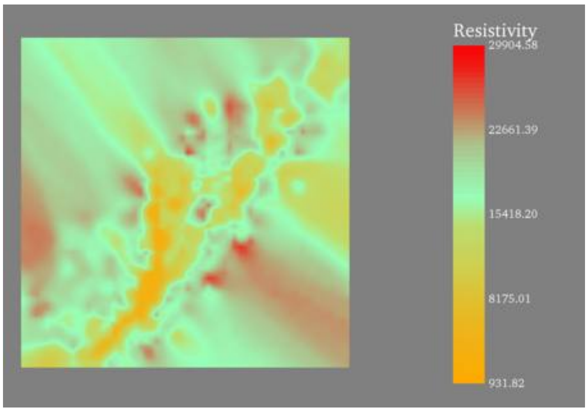
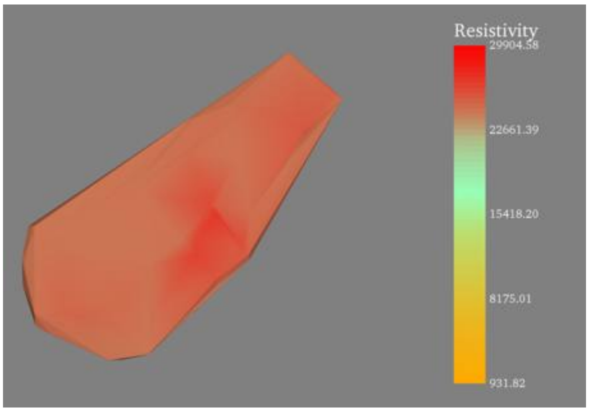


Figure 7.31: 3D point cloud representation of the ERT data

Both archaeologists decided to use the volume rendering representation to accomplish a first reading of the surveyed data, using colour mapping to visualize the different resistivity values and a scalar bar to interpret the colour associated to the range of registered resistivity values. They also agreed that the procedure did increase the understandability concerning the range and distribution of the scalar resistivity values over the spatial representation of the surveyed data (see figure 7.32a). However, the first archaeologists did consider the representation still insufficient to perceive a precise bounding volume of interest, while the second expert found it difficult to relate the volume representation to the spatial point cloud representation.



(a) Volume rendering based representation



(b) 3D Delaunay representation

Figure 7.32: ERT 3D representation

Since the first procedure to generate the spatial representation was not satisfactory for the archaeologists they proceeded using the 3D Delaunay triangulation procedure. Both agreed that this method undoubtedly produced a well defined convex hull of the bounding volume, however, it was difficult to understand the range and distribution of the scalar resistivity values (see figure 7.32b).

Clearly, for both archaeologists each methodology used to perform the spatial representation by itself was insufficient, but each procedure presented some benefit. Therefore, they sought to append both methodologies in one representation, but changed the opacity value of the two models of representation, in order to maintain the perception of the range and distribution of the scalar values and to be able to recognize the volume of interest. The result of these adjustments can be observed in figure 7.33, where the opacity value of the volume rendering representation was set to 30%, while the opacity of the Delaunay based reconstruction was set to 80%. The archaeologists were able to recognize both the bounding volume and the range and distribution of the resistivity values within that same volume.

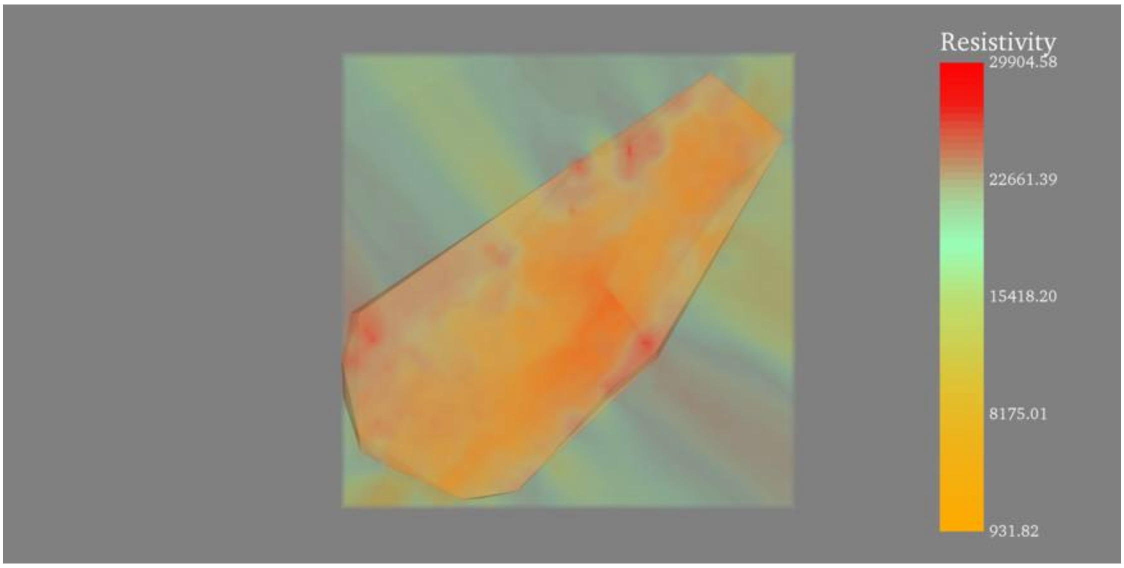
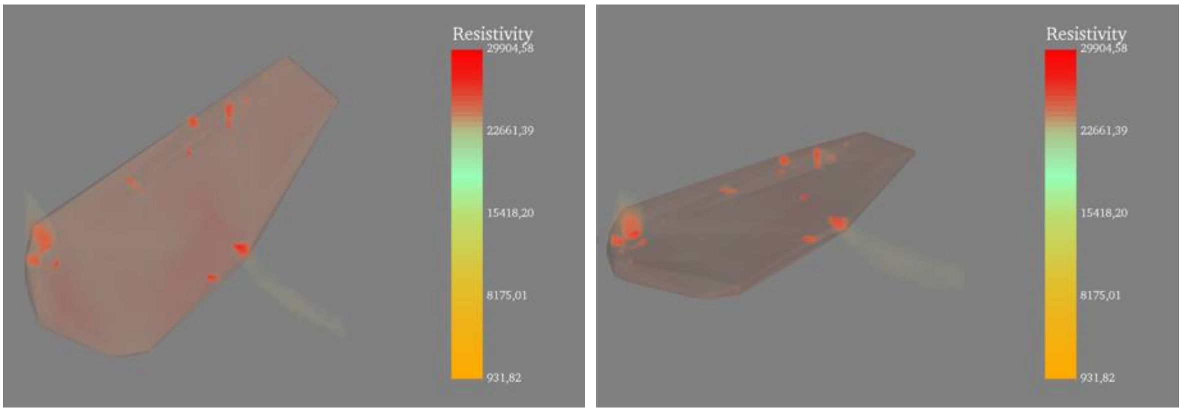


Figure 7.33: Hybrid spatial representation

Volumetric representation of anomalies

The first step of this task was to establish the resistivity range which represents the anomalies that might be related to archaeological features. This range of interest was provided by the experts who carried out the survey, according to their knowledge regarding environmental variables (soil moisture, climatology, geotechnics and mineralogical characterization) and taking into account the existence of historical structures and evidence. For the site used in this prototype evaluation, the values of interest for archaeological purposes range between 24.000 Ω.m and 25.000 Ω.m.

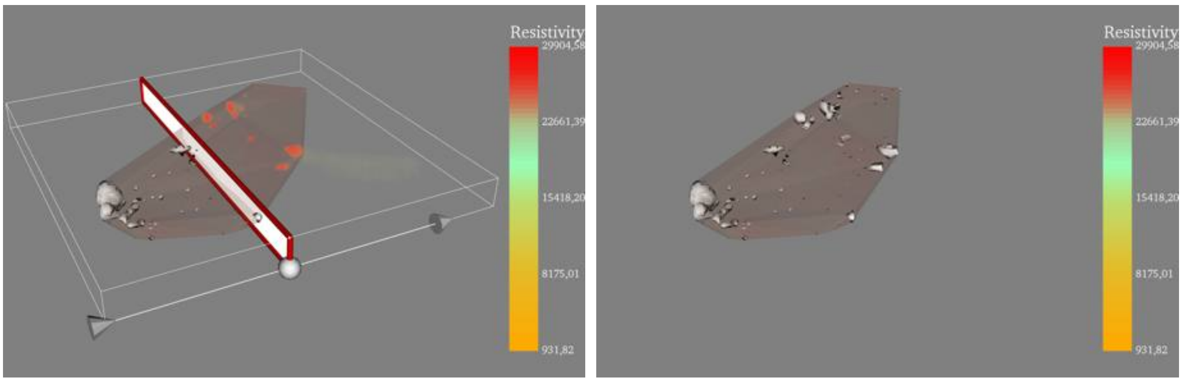
The next task of the archaeologists was to reset the opacity values associated with the volume rendering representation and with the Delaunay reconstruction. Both archaeologists set the opacity values of the resistivity within the range of interest to 100% while the values outside the range (with no potential interest for archaeologists) were set to values below 10%. Regarding the Delaunay-based reconstruction, the opacity of the 3D representation was set to values lower than 15%. The two archaeologists chose the opacity values freely to highlight the resistivity values that interested them. The other purpose was to maintain the visual perception of the initial volume of interest. Figure 7.34 unequivocally shows the bounding volume, with smaller volumes that represent clusters of resistivity values of potential archaeological interest. This 3D representation can be manipulated around all axes, without restrictions (see figure 7.34b).



(a) Top view

(b) Perspective view

Figure 7.34: Clusters with potential archaeological interest



(a) Using implicit plane widget to unveil volumes

(b) Enhanced perception of smaller volumes

Figure 7.35: Improving the cluster visualisation

In addition to the representation of the data shown in the previous figure, the archaeologists also extracted the geometry associated with the anomalies. They used the scalar-based data segmentation procedure to filter the clusters of resistivity into 3D surfaces and observed the result of this procedure by triggering the implicit plane widget and moving the plane freely over the volume. In this way they exposed the clusters (in grey) that represent anomalies with potential archaeological interest (see figure 7.35a) and noticed smaller volumes that are within the threshold condition, but that are not perceptible in the colour mapping method (see figure 7.35b).

7.3.5 Concluding remarks

The archaeologists easily understood the procedures for interacting with the ERT model and completed the proposed tasks without difficulty. To complete the two tasks they used the trackball type interaction, after experimenting with both interaction types. For the first task, both archaeologists used the camera mode, however in the second task the archaeologist E preferred the object model to interact independently with the different objects of the ERT representation.

	Archaeologist E	**Archaeologist F**
Joystick	-	-
Trackball	+	+
Camera	+	+
Object	+	-

Table 7.6: User-interaction evaluation of the third prototype

In the case of ERT data, to obtain a satisfactory representation of the bounding box of interest it was necessary to use volume rendering representation together with Delaunay 3D representation. The visual results of the Sapelos hillfort example seemed to make sense from an archaeological point of view because the volumes of interest displayed in the visualization environment appeared to indicate what looks to be the top defensive wall of the hillfort. In the same way, most of the smaller volumes of the inner area seemed to indicate the presence of buried buildings associated with the settlement's occupation. The sweeping plane accomplished a *cleaning* effect of separating what is strictly the geometric 3D representation of the volumes with potential archaeological interest from what can be considered noise. The result was a clearer representation of the potential structures of interest.

Working data from ERT surveys in order to evaluate non-visible archaeological features is neither linear or simple, mostly since there are a number of variables particular to each site that can substantially alter the electrical response to the features. The Sapelos' experiment revealed that the usage of geophysical data processed with 3D visualization methods can be a powerful tool to enhance the analysis of the volumetric data and help an archaeological analysis for a given site.

	Task 1	**Task 2**
Orientation	+	+
Dynamic scale	+/-	-
Colour mapping	+	+
Modelling	+	-
Scalar-based segmentation	-	+
Interactive cross-section	-	+
Interactive scale models	-	-
Computer Graphics rendering	+	+
Semantically supplemented 2D and 3D representations	+	+

Table 7.7: Visualization methods and strategies of the third prototype used to perform the proposed tasks

The two tasks were executed combining the computer graphics rendering strategy and the semantically supplemented 2D representation strategy. The interactive scale model strategy was not used on these tasks. All visualization methods associated with this prototype were used, although the dynamic scale procedure was not considered for the second task. The table 7.7 shows the relationship between visualization strategies, the visualization methods and the proposed tasks.

Chapter 8

Conclusions

This last chapter is mainly intended to provide answers that satisfy the research questions raised in *Section 1.3*. Therefore, this first section will present some conclusions to evaluate if this work effectively contributes in some way to the clarification of the proposed research questions.

As it is often the case, some responses to the research questions stimulate new ideas and, frequently, raise new interrogations. This was also the case for the present work, so the last section will be dedicated to the presentation of some thoughts to be worked on and explored in the future.

8.1 Research questions

The evaluation of the three prototypes was essential to conclude that the visualization techniques used are suitable for:

- increasing the perception of models that represent archaeological elements;
- producing new objects of archaeological interest;
- creating arbitrary sections for analysis purposes.

Nonetheless, the evaluation was also important to propose some solutions to the three research questions stated previously and that revolves around the importance of visualization techniques suitable for archaeological visualization.

8.1.1 What is required to successfully use more visualization techniques in archaeological visualization?

One of the problems mentioned in *section 1.2* was related to the use of only some advantages of the visualization techniques during the archaeological visualization process. This problem is fundamentally due to the fact that archaeologists seek to record data in a simple way, so the use of symbols/glyphs and colour would be sufficient techniques to visualize the data.

To successfully use more visualization techniques in archaeological visualization, this thesis proposes two distinct but complementary approaches:

- Use archaeological data acquisition methods that enable a higher-order acquisition – instead of the more traditional archaeological sketches that are recorded in bidimensional support, the experts should preferably use the data acquisition techniques that record the data in 3D support or higher. Also, having in mind the tridimensional reality of archaeological elements, the great advantage of using 3D data (or higher) is the completeness and soundness of the archaeological data representation;

- Associate visualization procedures to the 3D interaction techniques – besides associating visualization techniques directly to the archaeological 3D model, this work also associates visualization procedures to 3D widgets that interact with the 3D model to enhance perception about the archaeological data.

The advantages of higher-order dimensionality in the archaeological data are reflected throughout this work. As can be observed in tables 7.2, 7.5 and 7.7, in the case of models obtained from the archaeological interpretation and 2D drawings, few visualization techniques are used, while in data recorded using 3D acquisition techniques there is greater use of visualization techniques, able to extract new representations from the original data. This is what happens, for example, both when colour mapping procedures are activated (to assess the altimetry of a site or the distribution of resistivity values) or when generating new visual elements that represent data with potential archaeological interest (in the case of the formation of interpretation-free alignments of the archaeological site or in the case of volume generation from resistivity values with potential archaeological interest).

The use of interaction techniques for visual enhancement purposes are fundamental, particularly while dealing with 3D data. As illustrated in the evaluation of the first prototype, the basic translation, rotation and zoom features of the 3D interaction are important to improve the visual understanding of the virtual model. But this perception is even more increased when associating the cross-section procedure to an interactive 3D plane widget. This same advantage is also perceived by the users while using this same methodology to understand the surveyed ERT data in the third prototype. Also in the second prototype, while using the oblique lighting tool on the rock surface, or while using the mouse-based selection style to intuitively create regions of interest on a mesh surface, the overall perception of the surface model is improved.

8.1.2 How can visualization techniques be used to improve the visualization tools according to the archaeological needs?

Another problem stated previously in the first chapter is that visualization tools are normally not customized to the archaeological needs. This is because archaeologists often rely on existing tools for computer-supported archaeological visualization, instead of making the visualization tools depending on what the expert determines to be valuable for archaeological purposes.

To improve the visualization tools according to the archaeological needs, this work suggests the following practices:

- Use visualization techniques framed in the different levels of the suggested visualization model and that are similar or find parallelism in the traditional methodologies applied to represent and visualize archaeological data;

- Associate the visualization techniques according to the nature of the archaeological data – each type of archaeological data has distinct features and, therefore, diverse visualization necessities.

The immediate advantage of the first suggestion is that the usefulness of the visualization procedures for archaeological purposes is assured. Also, the users are perfectly aware regarding the complexity level of the visualization procedures and the amount of perception and of insight to be expected. As noticed during the evaluation of the proposed prototypes, the functional goal of these visualization procedures was effortlessly understood by the archaeologists and the visualization procedures were straightforwardly applied to accomplish the proposed tasks.

The second suggestion enables the creation of distinct visualization pipelines according to the nature of the archaeological data. This proposal was realized with the development of the three prototypes. Each prototype took into account the different nature and complexity of the data to define which visualization procedures best suited the data processing needs. For example, the first and third prototype both use clipping procedure associated with a plane widget, however, the first is used to create sections in the interpretation-based 3D model to understand the model, while the latter one is used to create sections in the hybrid representation of the ERT data to observe the contouring result. Similarly, colour mapping is used for different purposes in the second prototype and in the third prototype.

8.1.3 What kind of visualization procedures can be used to increase the usage of the 3D model features?

The last specified problem is concerned with the fact that mainly the visual features of the 3D representation of the archaeological data are used for archaeological analysis. More specifically, 3D models are often used only as an extension of two-dimensional images and other properties that are inherent to 3D models are ignored.

This work, naturally, also takes advantage of the visual features of 3D representations of archaeological data. Principally, in the case of user-assisted segmentation, the user uses his perception to define the areas he wants to segment in the original model. However, the perception can be increased by valuing properties such as altimetry, micro-topography of the object's surface or, in the case of higher-order dimensionality, the scalar values associated with the model. Therefore, to increase the use of the properties of the 3D model, particularly the models that result from the image-based 3D mesh and also from the ERT-based point cloud, this thesis proposes to:

- Evaluate thoroughly the properties of each 3D representation and understand the effect of each parameter of the visualization procedures, to visually enhance each property;
- Combine different visualization procedures on the same archaeological data.

The first proposal should be more understood as a way of proceeding prior to the use of any visualization procedure. It serves to reinforce the idea that the user must know his data very well and understand what additional insight he can gain. During the evaluation of the three prototypes, this aspect gained some relevance, as users realized that varying the parameterization of the visualization procedures, the data obtained also changed.

The advantage of combining two or more visualization procedures in the same set of archaeological data allows evidence of different features of the original model, but which are complementary. During the evaluation of the prototypes, this methodology was successfully used in both the second and the third prototype. In the second prototype, while generating the interpretation-free plan of the site, the users recognized the advantage of superimposing the non-realistic line model over the original 3D model. Also in the third prototype, the simultaneous representation of the data using triangulation and volumetric rendering was an important asset for understanding the extension of the surveyed data, while the simultaneous visualization of the scalar values using contouring algorithms and colour mapping was a precious help for archaeologist understand the volumes with potential archaeological interest.

8.2 Future Work

The main purpose of research is about understanding certain problems and finding out some answers that satisfy the research questions. However, some responses often raise new questions. It is therefore comprehensible that during the development of this work, some apprehensions and some suggestions arose that seem pertinent to complete this work.

The user-assisted segmentation of the image-based 3D meshes could be improved into a semi-automatic procedure focussed on the features (ex. micro-topography) of the mesh surface. The segmentation result should be be revised and adjusted by the experts, however the procedure itself would certainly speed-up definition of a region of interest.

Each prototype was evaluated by two experts which were concerned about the desktop-based platform of this archaeological visualization system. They all would have preferred mobile and/or a web-based platform to use this application. Therefore, this suggestion will be taken into consideration in the future and the entire archaeological visualization system, which is based on *VTK*, will be transformed into a responsive web-based visualization application. To implement this conversion, the *vtkWeb* and *vtk.js* libraries will be properly analyzed and evaluated, which ensure the same level of capabilities as the *VTK*.

The number of experts involved in the evaluation of the prototypes was somewhat reduced. Thus, it will be important to carry out a quantitative evaluation of the developed methods with a wider group of archaeologists, to evaluate the real impact of the proposed methods.

Another stimulating line of research would be integrating archaeological visualization procedures into an augmented/virtual reality system for virtual excavation training purposes and to establish different user-interaction experiences. The trainee could develop his skills in a fully controlled environment, preventing any accidental destruction in an archaeological site. However, to what extent would he be able to assimilate and develop the same skills as a trainee in a real-world context?

There are several geophysical survey methodologies that are normally carried out on archaeological sites. It was only possible to evaluate the prototype using an ERT survey of a site. However, future efforts should also consider the data from a GPR survey and from a magnetic survey.

Appendices

Appendix A

User survey

Virtual Representation and Visualization Methods in Archaeology

The importance of modelling and visualization in Archaeology, particularly in the dissemination of visual representations of archaeological interpretations, is widely recognized. However, it is also very important to understand the context in which computer-assisted tools, especially the ones for modelling and visualization, are used during the archaeological process.

This questionnaire is being conducted as part of a doctoral thesis in computer science, entitled "<i>Virtual Representation and Visualization Methods for Architectural and Contextual Information in Archaeological Sites</i>", in order to carry out a survey to analyze the usage of computer-assisted tools during the archaeological process.

Thank you very much for your generous attention.

Kind Regards,

Paulo Bernardes

Personal Data

1. **1. Age**

   ____

2. **2. Professional experience (years)**

   ____

3. **3. Professional category**

   ____

4. **4. Workplace**

   ____

5. **5. Employer**

   ____

6. **6. To which chronological period do the sites you have excavated belong**

   Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Paleolithic	◯	◯	◯	◯	◯
Mesolithic	◯	◯	◯	◯	◯
Neolithic	◯	◯	◯	◯	◯
Chalcolithic	◯	◯	◯	◯	◯
Bronze Age	◯	◯	◯	◯	◯
Iron Age	◯	◯	◯	◯	◯
Roman Period	◯	◯	◯	◯	◯
Suevic-Visigothic Period	◯	◯	◯	◯	◯
Middle Age	◯	◯	◯	◯	◯
Modern Age	◯	◯	◯	◯	◯
Contemporary Age	◯	◯	◯	◯	◯

Computer Assisted Tools in Archaeology

PHASE I - Archaeological Record (in the field)

7. **1.1 - Do you consider important to use computer or multimedia equipment for processing the archaeological record?**
Mark only one oval.

	1	2	3	4	5	
Not at all	⬭	⬭	⬭	⬭	⬭	Extremely

8. **1.2 - Why?**

9. **2.1 - Do you use computer or multimedia equipment for processing the archaeological record?**
Mark only one oval.

	1	2	3	4	5	
Never	⬭	⬭	⬭	⬭	⬭	Always

10. **2.2 - Why?**

11. **3.1 - Which computer or multimedia equipment do you use for processing the archaeological record?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
PDA	⬭	⬭	⬭	⬭	⬭
Smartphone (ex: iPhone)	⬭	⬭	⬭	⬭	⬭
Table PC (ex: iPad)	⬭	⬭	⬭	⬭	⬭
NetBook	⬭	⬭	⬭	⬭	⬭
Laptop	⬭	⬭	⬭	⬭	⬭
Digital Camera	⬭	⬭	⬭	⬭	⬭
Digital Video Camera	⬭	⬭	⬭	⬭	⬭
GPS	⬭	⬭	⬭	⬭	⬭
Total Station	⬭	⬭	⬭	⬭	⬭
Laser Scanner	⬭	⬭	⬭	⬭	⬭
Other (please, specify in 3.2)	⬭	⬭	⬭	⬭	⬭

12. **3.2 - Please, specify another computer or multimedia equipment you use for processing the archaeological record, that is not listed 3.1.**

____

13. **4.1 - Which computer assisted tools do you use for processing the archaeological record?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based Application (Backoffice)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Other (please specify in 4.2)					

14. **4.2 - Please, specify another computer assisted tool you use for processing the archaeological record, that is not listed in 4.1.**

____

15. **5.1 - Which computer assisted methods do you use for storing the archaeological record?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
File system (files are stored in a directory structure)					
Database					
Other (please specify in 5.2)					

16. **5.2 - Please, specify another computer assisted method you use for storing the archaeological record, that is not listed in 5.1.**

____

17. **6.1 - Which computer assisted tools do you use for visualizing the archaeological record?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based Application (Frontoffice)					
GIS (ArcGIS, MapGuide, gvSIG, etc)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Software system for visualization (VTK, AVS, etc.)					
Other (please specify in 6.2)					

18. **6.2 - Please, specify another computer assisted tool you use for visualizing the archaeological record, that is not listed in 6.1.**

PHASE II - Analysis and interpretation of the archaeological data (in the Lab)

19. **1.1 - Dou you consider important to use computer or multimedia equipment for analysis and interpretation purposes?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

20. **1.2 - Why?**

21. **2.1 - Do you use computer or multimedia equipment for analysis and interpretation purposes?**
Mark only one oval.

	1	2	3	4	5	
Never						Always

22. **2.2 - Why?**

23. **3.1 - Which computer or multimedia equipment do you use for analysis and interpretation purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Portable-PC					
Desktop-PC					
Graphical Workstation					
Other (please specify in 3.2)					

24. **3.2 - Please, specify another kind of computer or mulimedia equipment you use for analysis and interpretation purposes, that is not listed in 3.1.**

25. **4.1 - Which computer assisted tools do you use for analysis and interpretation purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based Application					
GIS (ArcGIS, MapGuide, gvSIG, etc)					
Archaeology Specific Software (ArchEd, Proleg, etc.)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Other (please specify in 4.2)					

26. **4.2 - Please, specify another computer assisted tool you use for analysis and interpretation purposes, that is not listed in 4.1.**

27. **5.1 - Which computer assisted methods do you use for storing the analysis and interpretation results?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
File system (files are stored in a directory structure)					
Database					
Other (please specify in 5.2)					

28. **5.2 - Please, specify another computer assisted method you use for storing analysis and interpretation results, that is not listed in 5.1.**

29. **6.1 - Which computer assisted tools do you use for visualizing the analysis and interpretation results of the archaeological record?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based Application (Frontoffice)					
GIS (ArcGIS, MapGuide, gvSIG, etc)					
Archaeology Specific Software (ArchEd, Proleg, etc.)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Software system for visualization (VTK, AVS, etc)					
Other (please specify in 6.2)					

30. **6.2 - Please, specify another computer assisted tool you use for visualizing the analysis and interpretation results of the archaeological record, that is not listed in 6.1.**

PHASE III - Publication of the archaeological data

31. **1.1 - Dou you consider important to use computer or multimedia equipment for publication purposes?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

32. **1.2 - Why?**

33. **2.1 - Do you use computer or multimedia equipment for publication purposes?**
Mark only one oval.

	1	2	3	4	5	
Never						Always

34. **2.2 - Why?**

35. **3.1 - Which computer or multimedia equipment do you use for producing contents for publication purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Portable-PC					
Desktop-PC					
Graphical Workstation					
Other (please specify in 3.2)					

36. **3.2 - Please, specify another computer or multimedia equipment you use for producing contents for publication purposes, that is not listed in 3.1.**

37. **4.1 - Which computer assisted tools do you use for producing contents for publication purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based Application					
GIS (ArcGIS, MapGuide, gvSIG, etc)					
Archaeology Specific Software (ArchEd, Proleg, etc.)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Multimedia tools (Dreamwaever, Flash, etc.)					
Video editing tool (Premier, VideoStudio, etc.)					
Other (please specify in 4.2)					

38. **4.2 - Please, specify another computer assisted tool you use for producing contents for publication purposes, that is not listed in 4.1**

39. **5.1 - Which computer assisted methods do you use for storing the contents for publication purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
File system (files are stored in a directory structure)					
Database					
Other (please specify in 5.2)					

40. **5.2 - Please, specify another computer assisted method you use for storing the contents for publication purposes, that is not listed in 5.1**

41. **6.1 - Which computer assisted tools do you use for visualizing the contents for publication purposes?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Text editor (WordPerfect, MS Word, Writer, etc.)					
Spreadsheet (MS Excel, Lotus 1-2-3, Calc, etc.)					
Database Management Program (MS Access, Base, etc.)					
Web-based application					
GIS (ArcGIS, MapGuide, gvSIG, etc)					
Archaeology Specific Software (ArchEd, Proleg, etc.)					
Vector Graphics Editor (Illustrator, CorelDRAW, Inkscape, etc.)					
Raster Graphics Editor (Photoshop, PaintShop, GIMP, etc.)					
CAD Software (AutoCAD, Microstation, etc.)					
3D Graphics Software (3DS Max, SketchUp, Blender, etc.)					
Multimedia Authoring tools (Director, Flash, etc.)					
Software system for visualization (VTK, AVS, etc.)					
Other (please specify in 6.2)					

42. **6.2 - Please, specify another computer assisted tool you use for visualizing the contents for publication purposes, that is not listed in 6.1.**

Computer-based Modelling tools in Archaeology

43. **1.1 - Dou you consider important to use computer-based modelling tools (ex: AutoCAD, Microstation, SketchUp, 3DS Max, Maya, Blender, etc.) in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

44. **1.2 - Why?**

45. **2.1 - Do you use computer-based modelling tools in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Never						Always

46. **2.2 - Why?**

47. **3.1 - Dou you use the drawing features (2D features) of the computer-based modelling tools in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Never	⬭	⬭	⬭	⬭	⬭	Always

48. **3.2 - Why?**

49. **4.1 - You use the 2D features for drawing:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Archaeological artefacts and finds	⬭	⬭	⬭	⬭	⬭
Sequences of deposits (cross-sections)	⬭	⬭	⬭	⬭	⬭
Plans	⬭	⬭	⬭	⬭	⬭
Structures	⬭	⬭	⬭	⬭	⬭
Other (please specify in 4.2)	⬭	⬭	⬭	⬭	⬭

50. **4.2 - Please, specify another item, that is not listed in 4.1**

51. **5.1 - You use these drawings for:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Post-processing of the archaeological record	⬭	⬭	⬭	⬭	⬭
Analysis & Interpretation	⬭	⬭	⬭	⬭	⬭
Research	⬭	⬭	⬭	⬭	⬭
Dissemination of knowledge	⬭	⬭	⬭	⬭	⬭
Other (please specify in 5.2)	⬭	⬭	⬭	⬭	⬭

52. **5.2 - Please, specify another purpose of these drawings, that is not listed in 5.1.**

53. **6.1 - Dou you use the modelling features (3D features) of the computer-based modelling tools in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Never						Always

54. **6.2 - Why?**

55. **7.1 - You use the 3D features for modelling:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Archaeological artefacts and finds					
Stratigraphic Units					
Structures					
Other (please specify in 7.2)					

56. **7.2 - Please specify what other kind of object you model using 3D features.**

57. **8.1 - You use these virtual 3D models for:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Post-processing of the archaeological record					
Analysis & Interpretation					
Research					
Dissemination of knowledge					
Other (please specify in 8.2)					

58. **8.2 - Please specify what other kind of usage you have for these 3D models.**

Computer-based visualization tools in Archaeology

59. **1.1 - Dou you consider important to use the traditional visualization tools (ex.: scale model, traditional archaeological drawing and illustration, etc.) for visualizing data in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

60. **1.2 - Why?**

61. **2.1 - Do you use traditional visualization tools for visualizing data in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Never						Always

62. **2.2 - Why?**

63. **3.1 - Which are the traditional visualization tools you use for visualizing data in archaeological?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Scale models					
Maps					
Archaeological drawing					
Archaeological illustration					
Other (please specify in 3.2)					

64. **3.2 - Please, specify another traditional visualization tool you use for visualizing data in archaeological, that is not listed in 3.1**

65. **4.1 - Dou you consider important to use computer-based tools (ex.: GIS Software, ArchEd, AutoCAD, 3DStudio, SketchUp, VRML/X3D, VTK, AVS, etc.) for visualizing data in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

66. **4.2 - Why?**

67. **5.1 - Do you use computer-based tools for visualizing data in archaeology?**
Mark only one oval.

	1	2	3	4	5	
Never	◯	◯	◯	◯	◯	Always

68. **5.2 - Why?**

69. **6 - Are you familiar with realistic visualization methods (based on accurate geometry) for visualizing archaeological data?**
Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Extremely

70. **7.1 - You use realistic visualization methods during the:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Post-processing of the archaeological record phase	◯	◯	◯	◯	◯
Analysis & Interpretation phase	◯	◯	◯	◯	◯
Research phase	◯	◯	◯	◯	◯
Dissemination of knowledge phase	◯	◯	◯	◯	◯
Other (please specify in 8.2)	◯	◯	◯	◯	◯

71. **7.2 - Please, specify another phase where you use realistic visualization methods for visualizing archaeological data, that is not listed in 7.1.**

72. **8.1 - You use realistic visualization methods to visualize:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Archaeological artefacts and finds	◯	◯	◯	◯	◯
Stratigraphic Units	◯	◯	◯	◯	◯
Structures	◯	◯	◯	◯	◯
Other (please specify in 7.2)	◯	◯	◯	◯	◯

73. **8.2 - Please, specify another archaeological object you visualize using realistic visualization methods, that is not listed in 8.1.**

74. **9 - Are you familiar with non-realistic visualization methods (not necessarily based on geometry) for visualizing archaeological data?**
Mark only one oval.

	1	2	3	4	5	
Not at all						Extremely

75. **10.1 - You use non-realistic visualization methods during the:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Post-processing of the archaeological record phase					
Analysis & Interpretation phase					
Research phase					
Dissemination of knowledge phase					
Other (please specify in 10.2)					

76. **10.2 - Please, specify another phase where you use non-realistic visualization methods for visualizing archaeological data, that is not listed in 10.1.**

____

77. **11.1 - You use non-realistic visualization methods to visualize:**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Archaeological artefacts and finds					
Stratigraphic Units					
Structures					
Other (please specify in 11.2)					

78. **11.2 - Please, specify another archaeological object you visualize using non-realistic visualization methods, that is not listed in 11.1.**

____

79. **12.1 - Which visualization techniques do you use for visualizing archaeological data?**
Mark only one oval per row.

	Never	Rarely	Sometimes	Often	Always
Table/Matrix					
Chart (Pie chart, bar chart, etc.)					
Graphs (Harris Matrix, etc.)					
Maps					
Color mapping (pseudo-color, etc.)					
Glyphing (symbols representing data)					
Cutting or slicing (create a cross-section)					
2D drawing					
3D Model					
Other (please specify in 12.2)					

80. **12.2 - Please, specify another visualization technique you use for visualizing archaeological data, that is not listed in 12.1.**

Bibliography

[1] Juan Barceló, Maurízio Forte, and Donald Sanders, "The Diversity of Archaeological Virtual Worlds", in *British Archaeological Reports - BAR International Series 843*, Juan Barceló, Maurizio Forte, and Donald Sanders, Eds. Virtual Reality in Archaeology - CAA'98, 1998.

[2] Matthew J. Douglass, Zachary R. Day, Jeremy C. Brunette, Peter Bleed, and Douglas Scott, "Virtual Reconstruction as Archaeological Observation: Embracing New Ways of Treating Sites, Places and Landscapes", *Advances in Archaeological Practice*, vol. 7, no. 2, pp. 127–139, 2019.

[3] Lawrence B. Conyers, *Ground-Penetrating Radar for Archaeology*, Altamira Press, third edition, 2013.

[4] Martin Carver, *Archaeological Investigation*, Routledge, 2013.

[5] Sorin Hermon and Joanna Nikodem, "3D Modelling as a Scientific Research Tool in Archaeology", *Layers of Perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA)*, pp. 1–6, 2008.
URL: *http://proceedings.caaconference.org/paper/38_hermon_nikodem_caa2007/*

[6] Sorin Hermon, "Scientific Method, *chaîne opératoire* and Visualization: 3D Modelling as a Research Tool in Archaeology", *Paradata and Transparency in Virtual Heritage*, pp. 13–22, 01 2012.

[7] Manuela Martins and Paulo Bernardes, "A Multi-disciplinary Approach for Research and Presentation of *Bracara Augusta's* Archaeological Heritage", *Archeologia e Calcolatori*, vol. 11, pp. 347–357, 2000.

[8] Adam Rabinowitz, "The Work of Archaeology in the Age of Digital Surrogacy", in *Visions of Substance: 3D Imaging in Mediterranean Archaeology*, Brandon R. Olson and Wiliam R. Caraher, Eds., chapter 4, pp. 27–42. The Digital Press at The University of North Dakota, Grand Forks, ND, 2015.
URL: *https://commons.und.edu/press-books/6/*

[9] Marcos Llobera, "Archaeological Visualization: Towards an Archaeological Information Science (AISc)", *Journal of Archaeological Method and Theory*, vol. 18, no. 3, pp. 193–223, 2011.

[10] Élise Meyer, Pierre Grussenmeyer, Jean-Pierre Perrin, Anne Durand, and Pierre Drap, "A Web Information System for the Management and the Dissemination of Cultural Heritage Data", *Journal of Cultural Heritage*, vol. 8, no. 4, pp. 396–411, 2007.

[11] Nicola Lercari, "3D Visualization and Reflexive Archaeology: A Virtual Reconstruction of Çatalhöyük History Houses", *Digital Applications in Archaeology and Cultural Heritage*, vol. 6, pp. 10–17, 2017, The Past now showing in 3D: case studies in 3D archaeology.
URL: *http://www.sciencedirect.com/science/article/pii/S2212054816300327*

[12] Corinna Rossi, Cristiana Achille, Francesco Fassi, Francesca Lori, Fabrizio Rechichi, and Fausta Fiorillo, "Digital Workflow to Support Archaeological Excavation: From the 3D Survey to the Websharing of Data", in *Innovative Models for Sustainable Development in Emerging African Countries*, Niccolò Aste, Stefano Della Torre, Cinzia Talamo, Rajendra Singh Adhikari, and Corinna Rossi, Eds., pp. 149–157. Springer International Publishing, Cham, 2020.

[13] George L. Cowgill, "Computer Applications in Archaeology", in *Proceedings of the November 14-16, 1967, Fall Joint Computer Conference*, New York, NY, USA, 1967, AFIPS '67 (Fall), pp. 331–337, ACM.
URL: *http://doi.acm.org/10.1145/1465611.1465654*

[14] Robert G. Chenhall, "The Impact of Computers on Archaeological Theory: an Appraisal and Projection", *Computers and the Humanities*, vol. 3, no. 1, pp. 15–24, Sep 1968.
URL: *https://doi.org/10.1007/BF02395445*

[15] Robert Whallon, "The Computer in Archaeology: a Critical Survey", *Computers and the Humanities*, vol. 7, no. 1, pp. 29–45, Sep 1972.
URL: *https://doi.org/10.1007/BF02403759*

[16] Robert Sablatnig and Christian Menard, "3D Reconstruction of Archaeological Pottery Using Profile Primitives", *Proc. of Intl. Workshop on Synthetic-Natural Hybrid Coding and Three-Dimensional Imaging*, pp. 93–96, 1997.

[17] Maic Masuch, Bert Freudenberg, Babette Ludowici, Sebastian Kreiker, and Thomas Strothotte, "Virtual Reconstruction of Medieval Architecture", *Proceedings of Eurographics 1999, Short Papers and Demos*, pp. 87–90, 1999.
URL: *http://www.eg.org/EG/DL/Conf/EG99/short*

[18] Charalambos Ioannidis, Chryssy Potsio, Sofia Soile, and John Badekas, "Detailed 3D Representation of Archaeological Sites", *International Archives of the Photogrammetry and Remote Sensing*, vol. XXXIII, no. Part B5, pp. 642–649, 2000.

[19] Martin Belcher, Alan Chalmers, Andrew Harrison, and Simon Stoddart, "Teaching the Visualization of Landscapes - Approaches in Computer based learning for Archaeologists", *Analecta Praehistorica Leidensia*, , no. 28, pp. 483–487, 1996.

[20] Dave Sims, "Archaeological Models: Pretty Pictures or Research Tools?", *Computer Graphics and Applications, IEEE*, vol. 17, no. 1, pp. 13–15, jan/feb 1997.

[21] Donald H. Sanders, "Virtual Worlds for Archaeological Research and Education", *Bar International Series*, vol. 750, no. November, pp. 265, 1999.

[22] Alonzo C. Addison, "Emerging Trends in Virtual Heritage", *IEEE Multimedia*, vol. 7, no. 2, pp. 22–25, 2000.

[23] Julian D. Richards, "Recent Trends in Computer Applications in Archaeology", *Journal of Archaeological Research*, vol. 6, no. 4, pp. 331–382, 1998.

[24] Paul Reilly, "Towards a Virtual Archaeology", in *Proceedings of the 18th CAA conference*, Kris Lockyear and Sebastian Rahtz, Eds. 1991, BAR International Series (S565), Tempvs Reparatvm, Oxford, UK.

[25] Thomas L. Evans and Patrick Daly, *Digital Archaeology: Bridging Method and Theory*, Routledge, Taylor & Francis Group, London and New York, London, 2006.

[26] Maurízio Forte, "Introduction to Cyber-Archaeology", *BAR International Series 2177*, pp. 9–14, 2010.

[27] Nick Ryan, "Documenting and Validating Virtual Archaeology", *Archeologia e Calcolatori*, vol. 12, pp. 245–273, 2001.

[28] Ezra Zubrow, *Digital Archaeology: A historical context*, pp. 10–31, In Evans and Daly [25], 2006.

[29] Leore Grosman, "Reaching the Point of No Return: The Computational Revolution in Archaeology", *Annual Review of Anthropology*, vol. 45, no. 1, pp. 129–145, 2016.
URL: *http://www.annualreviews.org/doi/10.1146/annurev-anthro-102215-095946*

[30] Víctor M. F. Martínez, *Teoría y Método de la Arqueologia*, Editorial Sínteses, Madrid, 2 edition, May 2000.

[31] Philip Barker, *Techniques of Archaeological Excavation*, B. T. Batsford Ltd., London, third edition edition, 1993.

[32] Kevin Greene and Tom Moore, *Archaeology: An Introduction*, Routledge, Taylor & Francis Group, London and New York, fifth edition, 2010.

[33] Edward C. Harris, "The Concept of Stratigraphy in Archaeology", in *Principles of Archaeological Stratigraphy (Second Edition)*, Edward C. Harris, Ed., pp. 7–13. Academic Press, London, second edition edition, 1989.
URL: *http://www.sciencedirect.com/science/article/pii/B9780123266514500109*

[34] André De Naeyer, S. P. Arroyo, and J. R. Blanco, "Krakow Charter 2000: Principles for Conservation and Restoration of Built Heritage", 2000.

[35] ICOMOS, "ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites", *International Journal of Cultural Property*, vol. 15, no. 04, pp. 377–383, 2008.

[36] EPOCH, "The London Charter", Tech. Rep. February, King's College London, 2009.
URL: *http://www.londoncharter.org/*

[37] Hugh Denard, "A new introduction to the London Charter", *Paradata and Transparency in Virtual Heritage Digital Research in the Arts and Humanities Series*, pp. 57–71, 2012.
URL: *http://www.academia.edu/download/31017459/ch6_denard.pdf*

[38] Victor Manuel Lopez-Menchero and Alfredo Grande, "The Principles of the Seville Charter", *Proceedings XXIIIrd International CIPA Symposium*, pp. 12–16, 2011.
URL: *http://congressgate.com/cipa/proceedings/pdfs/B-2 Seville charter/Lopez Menchero.pdf*

[39] Massimiliano Pieraccini, Gabriele Guidi, and Carlo Atzeni, "3D Digitizing of Cultural Heritage", *Journal of Cultural Heritage*, vol. 2, no. 1, pp. 63–70, 2001.

[40] Michael Ashley López, "Managing the Real with the Virtual: a Role for digital Media Recording in Archaeological Fieldwork", In Arnold et al. [148].

[41] George Pavlidis, Anestis Koutsoudis, Fotis Arnaoutoglou, Vassilios Tsioukas, and Christodoulos Chamzas, "Methods for 3D Digitization of Cultural Heritage", *Journal of Cultural Heritage*, vol. 8, no. 1, pp. 93–98, 2007.

[42] Timothy Nuttens, Philippe De Maeyer, Alain De Wulf, Rudi Goossens, and Cornelis Stal, "Terrestrial Laser Scanning and Digital Photogrammetry for Cultural Heritage : an Accuracy Assessment", *4th International Workshop on 3D Geo-Information*, 2009.

[43] Sorin Hermon, Hamudi Khalaily, Ianir Milevski, Nicola Amico, Giancarlo Iannone, and Nimrod Getzov, "Archaeological Field Documentation and Architectonic Analysis - a 3D Approach. Ein Zippori as Study Case", in *Proceedings of VAST12: The 13th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*,

David B. Arnold, Jaime Kaminski, Franco Niccolucci, and André Stork, Eds., Brighton, Nov. 2012, pp. 113–120, Eurographics Association.

[44] Jeroen De Reu, Gertjan Plets, Geert Verhoeven, Philippe De Smedt, Machteld Bats, Bart Cherrett, Wouter De Maeyer, Jasper Deconynck, Davy Herremans, Pieter Laloo, Marc Van Meirvenne, and Wim De Clercq, "Towards a Three-dimensional Cost-effective Registration of the Archaeological Heritage", *Journal of Archaeological Science*, vol. 40, no. 2, pp. 1108–1121, 2013.

[45] Matt Westoby, James Brasington, Neil Glasser, Michael Hambrey, and John Reynolds, "'Structure-from-Motion' Photogrammetry: a Low-cost, Effective Tool for Geoscience Applications", *Geomorphology*, vol. 179, pp. 300–314, 2012.

[46] Ralf Hesse, "Combining Structure-from-Motion with High and Intermediate Resolution Satellite Images to Document Threats to Archaeological Heritage in Arid Environments", *Journal of Cultural Heritage*, vol. 16, no. 2, pp. 192–201, Mar. 2015.

[47] Michael Zollhöfer, Christian Siegl, Mark Vetter, Boris Dreyer, Marc Stamminger, Serdar Aybek, and Frank Bauer, "Low-Cost Real-Time 3D Reconstruction of Large-Scale Excavation Sites", *Journal on Computing and Cultural Heritage*, vol. 9, no. 1, pp. 2:1–2:20, Nov. 2015.
URL: *http://doi.acm.org/10.1145/2770877*

[48] Thais de Souza, Guilherme Mota, and Guadalupe Campos, "Digitalização 3D do Património Arqueológico Metálico usando o Kinect", in *Preservação do Patrimônio Arqueológico: desafios e estudos de caso*, pp. 192–219. Museu de Astronomia e Ciências Afins, Rio de Janeiro, Brasil, 2017.

[49] Annabelle Davis, David Belton, Petra Helmholz, Paul Bourke, and Jo McDonald, "Pilbara Rock Art: Laser Scanning, Photogrammetry and 3D Photographic Reconstruction as Heritage Management Tools", *Heritage Science*, vol. 5, no. 1, pp. 1–16, July 2017.
URL: *https://doi.org/10.1186/s40494-017-0140-7*

[50] Karsten Lambers and Fabio Remondino, "Optical 3D Measurement Techniques in Archaeology: Recent Developments and Applications", in *Layers of perception. Proceedings of the 35 th International conference on Computer Applications and Quantitative*

Methods in Archaeology (CAA), Berlin, Germany, April 2 - 6, 2007, Axel Posluschny, Karsten Lambers, and I. Herzog, Eds., Bonn, 2008, pp. 27–35, Habelt.

[51] Alan Federman, Mario Santana Quintero, Stefanie Kretz, Julie Gregg, M. Lengies, Christian Ouimet, and Jean-François Laliberté, "UAV Photgrammetric Workflows: a Best Practice Guideline", *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 62W5, pp. 237–244, Aug. 2017.

[52] Simon Haegler, Pascal Müller, and Luc Van Gool, "Procedural Modeling for Digital Cultural Heritage", *EURASIP Journal on Image and Video Processing*, vol. 2009, 2009.

[53] Marie Saldaña, "An Integrated Approach to the Procedural Modeling of Ancient Cities and Buildings", *Digital Scholarship in the Humanities*, vol. 30, pp. i148–i163, 2015.

[54] Maurice Murphy, Eugene McGovern, and Sara Pavia, "Historic Building Information Modelling (HBIM)", *Structural Survey*, vol. 27, no. 4, pp. 311–327, 2009.
URL: *http://www.emeraldinsight.com/doi/10.1108/02630800910985108*

[55] S. Logothetis, A. Delinasiou, and E. Stylianidis, "Building Information Modelling for Cultural Heritage: a Review", *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. II-5/W3, pp. 177–183, 2015.
URL: *https://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/II-5-W3/177/2015/*

[56] Nurul Shahida Sulaiman, Erna Warnita Bachad, Albert K. Chong, Zulkepli Majid, and Halim Setan, "Generating Three-Dimensional Photo-Realistic Model of Archaeological Monument via Multi-sensors' Data Integration", *International Journal of Research in Engineering and Technology*, vol. 02, no. 10, pp. 362–373, 2013.

[57] Susie Green, Andrew Bevan, and Michael Shapland, "A Comparative Assessment of Structure from Motion Methods for Archaeological Research", *Journal of Archaeological Science*, vol. 46, pp. 173–181, 2014.
URL: *http://www.sciencedirect.com/science/article/pii/S030544031400079X*

[58] Marco Callieri, Guido Ranzuglia, Matteo Dellepiane, Paolo Cignoni, and Roberto Scopigno, "Meshlab as a Complete Open Tool for the Integration of Photos and Colour

with High-Resolution 3D Geometry Data", in *CAA 2012 Conference Proceedings*. 2013, pp. 406–416, Pallas Publications - Amsterdam University Press (AUP).
URL: *http://vcg.isti.cnr.it/Publications/2013/RCDCS13*

[59] Jenniffer S. Lewin and Mark D. Gross, "Resolving Archaeological Site Data with 3D Computer Modeling: the Case of Ceren", *Automation in Construction*, vol. 6, no. 4, pp. 323–334, 1997.
URL: *http://www.sciencedirect.com/science/article/pii/S0926580597000459*

[60] Francesco Gabellone, "Ancient Contexts and Virtual Reality: From Reconstructive Study to the Construction of Knowledge Models", *Journal of Cultural Heritage*, vol. 10, no. Supplement 1, pp. e112 – e117, 2009.

[61] Peter K. Allen, Alejandro Troccoli, Benjamin Smith, Stephen Murray, Ioannis Stamos, and Marius Leordeanu, "New Methods for Digital Modeling of Historic Sites", *IEEE Computer Graphics and Applications*, vol. 23, pp. 32–41, 2003.

[62] Jonathan Maïm, Simon Haegler, Barbara Yersin, Pascal Müller, Daniel Thalmann, and Luc J. Van Gool, "Populating Ancient Pompeii with Crowds of Virtual Romans", in *Proceedings of VAST 2007: The 8th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, David B. Arnold, Franco Niccolucci, and Alan Chalmers, Eds., Brighton, United Kingdom, Nov. 2007, pp. 109–116, Eurographics Association.

[63] Mariana Danielová, Holger Kumke, and Stefan Peters, "3D Reconstruction and Uncertainty Modelling Using Fuzzy Logic of Archaeological Structures: Applied to the Temple of Diana in Nemi, Italy", *Cartographica: The International Journal for Geographic Information and Geovisualization*, vol. 51, no. 3, pp. 137–146, 2016.

[64] J. A. Benavides López, G. Aranda Jiménez, M. Sánchez Romero, E. Alarcón García, S. Fernández Martín, A. Lozano Medina, and J. A.Esquivel Guerrero, "3D Modelling in Archaeology: the Application of Structure from Motion Methods to the Study of the Megalithic Necropolis of Panoria (Granada, Spain)", *Journal of Archaeological Science: Reports*, vol. 10, pp. 495–506, 2016.

[65] Andrea Jalandoni, Inés Domingo, and Paul S.C. Taçon, "Testing the Value of Low-cost Structure-from-Motion (SfM) Photogrammetry for Metric and Visual Analysis of Rock Art", *Journal of Archaeological Science: Reports*, vol. 17, pp. 605–616, 2018.

[66] Martin Kampel and Robert Sablatnig, "An Automated Pottery Archival and Reconstruction System", *Journal of Visualization and Computer Animation*, vol. 14, no. 3, pp. 111–120, 2003.

[67] Avshalom Karasik and Uzy Smilansky, "3D Scanning Technology as a Standard Archaeological Tool for Pottery Analysis: Practice and Theory", *Journal of Archaeological Science*, vol. 35, no. 5, pp. 1148–1168, 2008.

[68] Avshalom Karasik and Uzy Smilansky, "Computerized Morphological Classification of Ceramics", *Journal of Archaeological Science*, vol. 38, no. 10, pp. 2644–2657, 2011.
URL: *http://www.sciencedirect.com/science/article/pii/S030544031100183X*

[69] Shu-Kam Chow and Kwok-Leung Chan, "Reconstruction of Photorealistic 3D Model of Ceramic Artefacts for Interactive Virtual Exhibition", *Journal of Cultural Heritage*, vol. 10, no. 2, pp. 161–173, 2009.

[70] Caterina Balletti, Martina Ballarin, and Francesco Guerra, "3D printing: State of the Art and Future Perspectives", *Journal of Cultural Heritage*, vol. 26, pp. 172–182, 2017.

[71] Roberto Scopigno, Paolo Cignoni, Nico Pietroni, Marco Callieri, and Matteo Dellepiane, "Digital Fabrication Techniques for Cultural Heritage: A Survey", *Computer Graphics Forum*, vol. 36, pp. 6–21, 2017.
URL: *http://doi.wiley.com/10.1111/cgf.12781*

[72] Louis-Martin Losier, Jacynthe Pouliot, and Michel Fortin, "3D Geometrical Modeling of Excavation Units at the Archaeological Site of Tell 'Acharneh (Syria)", *Journal of Archaeological Science*, vol. 34, no. 2, pp. 272–288, 2007.

[73] Ronald Valente, Raffaella Brumana, Daniela Oreni, Fabrizio Banfi, Luigi Barazzetti, and Mattia Previtali, "Object-oriented Approach for 3D Archaeological Documentation", *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2/W5, pp. 707–712, 2017.

URL: *https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W5/707/2017/*

[74] Damian Green, John Cosmas, Take Itagaki, Marc Waelkens, Roland DeGeest, and Edward Grabczewski, "A real time 3D stratigraphic visual simulation system for archaeological analysis and hypothesis testing", in *Proceedings of the 2001 Conference on Virtual Reality, Archeology, and Cultural Heritage*, David B. Arnold, Alan Chalmers, and Dieter W. Fellner, Eds., Glyfada, Greece, Nov. 2001, pp. 271–278, ACM.

[75] Damian Green, John Cosmas, and Take Itagaki, "Visualizing Legacy Stratigraphic Data from Archaeological Handbooks", in *Proceedings of the 1st International Symposium on 3D Data Processing Visualization and Transmission (3DPVT 2002)*, Padova, Italy, June 2002, pp. 750–753, IEEE Computer Society.

[76] Markus Grabner, Ralph Wozelka, Manish Mirchandani, and Konrad Schindler, "Web-based visualization of virtual archaeological sites", in *Proceedings of the 4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, David Arnold, Alan Chalmers, and Franco Niccolucci, Eds. 2003, The Eurographics Association.

[77] Nicola Lercari, Emmanuel Shiferaw, Maurizio Forte, and Regis Kopper, "Immersive Visualization and Curation of Archaeological Heritage Data: Çatalhöyük and the Dig@IT App", *Journal of Archaeological Method and Theory*, vol. 25, no. 2, pp. 368–392, jun 2018.
URL: *http://link.springer.com/10.1007/s10816-017-9340-4*

[78] Maurizio Forte, "3D Archaeology. New Perspectives and Challenges. The example of Çatalhöyük", *Near Eastern Archaeology*, vol. 2, pp. 1–29, 2014.

[79] Maurizio Forte, Nicolo Dell'Unto, Kristina Jonsson, and Nicola Lercari, *Interpretation Process at Çatalhöyük using 3D*, vol. 1 of *Themes in Contemporary Archaeology*, pp. 43–57, Maney, 2015, Published for the European Association of Archaeologists.

[80] Maurizio Forte, "Virtual Reality, Cyberarchaeology, and Teleimmersive Archaeology", in *3D Recording and Modelling in Archaeology and Cultural Heritage: Theory and Best Practices*, S. Campana and F. Remondino, Eds. BAR ARCHAEOPRESS, Jan. 2013.

[81] Tarek Azzam, Stephanie Evergreen, Amy A. Germuth, and Susan J. Kistler, "Data Visualization and Evaluation", *New Directions for Evaluation*, vol. 2013, no. 139, pp. 7–32, 2013.

[82] H. Gray Funkhouser, "A Note on a Tenth Century Graph", *Osiris*, vol. 1, pp. 260–262, 1936.
URL: *https://doi.org/10.1086/368425*

[83] Michael Friendly, "A Brief History of Data Visualization", in *Handbook of Computational Statistics: Data Visualization*, C. Chen, W. Härdle, and A. Unwin, Eds., vol. III, pp. 15–56. Springer-Verlag, Heidelberg, 2008.

[84] Will Schroeder, Ken Martin, and Bill Lorensen, *The Visualization Toolkit - An Object-Oriented Approach to 3D Graphics*, Kitware Inc., fourth edition, 2006.

[85] Stephan Diehl, *Software Visualization - Visualizing the Structure, Behaviour, and Evolution of Software*, Springer, 2007.

[86] Kenneth Moreland, "A Survey of Visualization Pipelines", *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 3, pp. 367–378, March 2013.

[87] Alessandro E. Foni, George Papagiannakis, and Nadia Magnenat-Thalmann, "A Taxonomy of Visualization Strategies for Cultural Heritage Applications", *Journal on Computing and Cultural Heritage*, vol. 3, pp. 1:1–1:21, July 2010.

[88] Paul Reilly, "Data Visualization in Archaeology", *IBM Systems Journal*, vol. 28, pp. 569–579, November 1989.

[89] Diego Gutierrez, Veronica Sundstedt, Fermin Gomez, and Alan Chalmers, "Dust and Light: Predictive Virtual Archaeology", *Journal of Cultural Heritage*, vol. 8, no. 2, pp. 209 – 214, 2007.

[90] Markos Katsianis, Spyros Tsipidis, Kostas Kotsakis, and Alexandra Koussoulakou, "A 3D Digital Workflow for Archaeological Intra-site Research using GIS", *Journal of Archaeological Science*, vol. 35, no. 3, pp. 655 – 667, 2008.

[91] Eben Gay, David Cooper, Benjamin Kimia, Gabriel Taubin, Katarina Galor, Donald Sanders, and Andrew Willis, "REVEAL Intermediate Report", in *2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition - Workshops*, June 2010, pp. 1–6.

[92] Spyridon Tsipidis, Alexandra Koussoukakou, and Kostas Kotsakis, "Geovisualization and Archaeology: supporting Excavation Site Research", in *Advances in Cartography and GIScience*, Anne Ruas, Ed. 2011, vol. 2 of *Selection from ICC 2011*, pp. 85–108, Springer Verlag.

[93] Edward González-Tennant, "Recent Directions and Future Developments in Geographic Information Systems for Historical Archaeology", *Historical Archaeology*, vol. 50, no. 3, pp. 24–49, Sep 2016.
URL: *https://doi.org/10.1007/BF03377332*

[94] Rebecca Bennett, David J. Zielinski, and Regis Kopper, "Comparison of interactive environments for the archaeological exploration of 3D landscape data", in *2014 IEEE VIS International Workshop on 3DVis (3DVis)*, Nov 2014, pp. 67–71.

[95] Eileen Vote, Daniel Acevedo, David H. Laidlaw, and Martha Joukowsky, "Discovering Petra: Archaeological Analysis in VR", *IEEE Computer Graphics and Applications*, vol. 22, no. 5, pp. 38–50, September/October 2002.

[96] Hrvoje Benko, Edward W. Ishak, and Steven Feiner, "Collaborative Mixed Reality Visualization of an Archaeological Excavation", in *Third IEEE and ACM International Symposium on Mixed and Augmented Reality, 2004. ISMAR 2004.*, Arlington, VA, USA, Nov. 2004, pp. 132–140, IEEE Computer Society.

[97] Heather Richards-Rissetto, "What can GIS+3D mean for Landscape Archaeology?", *Journal of Archaeological Science*, vol. 84, pp. 10–21, August 2017.

[98] Giacomo Landeschi, "Rethinking GIS, Three-dimensionality and Space Perception in Archaeology", *World Archaeology*, vol. 51, no. 1, pp. 17–32, 2019.
URL: *https://doi.org/10.1080/00438243.2018.1463171*

[99] Vid Petrovic, Aaron Gidding, Tom Wypych, Falko Kuester, Thomas DeFanti, and Thomas Levy, “Dealing with Archaeology’s Data Avalanche”, *Computer*, vol. 44, pp. 56–60, July 2011.

[100] Nicoló Dell’Unto, Giacomo Landeschi, Anne Marie Leander Touati, Matteo Dellepiane, Marco Callieri, and Daniele Ferdani, “Experiencing Ancient Buildings from a 3D GIS Perspective: a Case Drawn from the Swedish Pompeii Project”, *Journal of Archaeological Method and Theory*, vol. 23, no. 1, pp. 73–94, 2016.
URL: *https://doi.org/10.1007/s10816-014-9226-7*

[101] Paulo Bernardes, Natália Botica, Fernanda Magalhães, and Manuela Martins, “Uma Plataforma de Representação e Divulgação da História Urbana de Braga”, *Férvedes*, vol. 8, pp. 453–461, 2015.
URL: *https://dialnet.unirioja.es/servlet/articulo?codigo=6154967*

[102] Thomas Strothotte, Maic Masuch, and Tobias Isenberg, “Visualizing Knowledge about Virtual Reconstructions of Ancient Architecture”, in *CGI 99: Proceedings of the International Conference on Computer Graphics*, Canmore, Alberta, Canada, June 1999, pp. 36–43, IEEE Computer Society.

[103] Maria Roussou and George Drettakis, “Photorealism and Non-Photorealism in Virtual Heritage Representation”, In Arnold et al. [148], pp. 51–60.

[104] Torre Zuk, Sheelagh Carpendale, and William Glanzman, “Visualizing Temporal Uncertainty in 3D Virtual Reconstructions”, in *VAST 2005: The 6th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage, Incorporating 3rd EUROGRAPHICS Workshop on Graphics and Cultural Heritage*, M. Mudge, N. Ryan, and R. Scopigno, Eds., Pisa, Italy, Nov. 2005, pp. 99–106, Eurographics Publications.

[105] Scott Houde, Sheila Bonde, and David H. Laidlaw, “An Evaluation of Three Methods for Visualizing Uncertainty in Architecture and Archaeology”, in *Proceedings of the 2015 IEEE Scientific Visualization Conference (SciVis)*, Chicago, Illinois, USA, Oct 2015, pp. 149–150, IEEE.

[106] Tao Luo, Renju Li, and Hongbin Zha, "3D Line Drawing for Archaeological Illustration", *International Journal of Computer Vision*, vol. 94, no. 1, pp. 23–35, 2011.

[107] Renju Li, Tao Luo, Hongbin Zha, and Wei Lu, "Computer-Assisted Archaeological Line Drawing", *Computer*, vol. 44, pp. 62–65, July 2011.

[108] Gur Harary and Ayellet Tal, "3D Euler Spirals for 3D Curve Completion", in *Proceedings of the 26th ACM Symposium on Computational Geometry*, Jack Snoeyink, Mark de Berg, Joseph S. B. Mitchell, Günter Rote, and Monique Teillaud, Eds., Snowbird, Utah, USA, June 2010, pp. 393–402, ACM.

[109] Xuejin Chen, Yann Morvan, Yu He, Julie Dorsey, and Holly E. Rushmeier, "An Integrated Image and Sketching Environment for Archaeological Sites", in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, CVPR Workshops 2010*, San Francisco, CA, USA, June 2010, pp. 35–42, IEEE Computer Society.
URL: *https://doi.org/10.1109/CVPRW.2010.5543514*

[110] Matthew Magnani, "Three-Dimensional Alternatives to Lithic Illustration", *Advances in Archaeological Practice*, vol. 2, no. 4, pp. 285–297, 2014.

[111] Christine Morris, Alan Peatfield, and Brendan O'Neill, "Figures in 3D: Digital Perspectives on Cretan Bronze Age Figurines", *Open Archaeology*, vol. 4, no. 1, pp. 50–61, 2018.
URL: *https://www.degruyter.com/view/journals/opar/4/1/article-p50.xml*

[112] Ralph Lengler and Martin J. Eppler, "Towards a Periodic Table of Visualization Methods of Management", in *Proceedings of the 2007 IASTED Conference on Graphics and Visualization in Engineering*, Clearwater, Florida, USA, 2007, GVE 07, pp. 83–88, ACTA Press.

[113] G. Harvey, *Excel 2013 all-in-one for dummies*, 2013.

[114] Carl Vilbrandt, Galina Pasko, Alexander Pasko, Pierre-Alain Fayolle, Turlif Vilbrandt, Janet R. Goodwin, James M. Goodwin, and Tosiyasu L. Kunii, "Cultural Heritage Preservation Using Constructive Shape Modeling", *Computer Graphics Forum*, vol. 23,

no. 1, pp. 25–41, Mar. 2004.
URL: *https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-8659.2004.00003.x*

[115] Jesus Fernández-Hernandez, D. González-Aguilera, Pablo Rodríguez-Gonzálvez, and J. Mancera-Taboada, "Image-Based Modelling from Unmanned Aerial Vehicle (UAV) Photogrammetry: An Effective, Low-Cost Tool for Archaeological Applications", *Archaeometry*, vol. 57, no. 1, pp. 128–145, Feb. 2015.
URL: *https://onlinelibrary.wiley.com/doi/abs/10.1111/arcm.12078*

[116] Kenton McHenry and Peter Bajcsy, "An overview of 3D data content, file formats and viewers", Tech. Rep., National Center for Supercomputing Applications, 2008.

[117] Meng Heng Loke, *Tutorial: 2-D and 3-D electrical imaging surveys*, Geotomo Software, Inc, 2012.

[118] Peter G. Dorrell, "Principles of Close-up Photography", in *Photography in Archaeology and Conservation*, pp. 177–197. Cambridge University Press, Cambridge, 9 1994.

[119] Mark Mudge, Tom Malzbender, Alan Chalmers, Roberto Scopigno, James Davis, Oliver Wang, Prabath Gunawardane, Michael Ashley, Martin Doerr, Alberto Proença, and João Barbosa, "Image-Based Empirical Information Acquisition, Scientific Reliability, and Long-Term Digital Preservation for the Natural Sciences and Cultural Heritage", in *Eurographics 2008 - Tutorials*, Maria Roussou and Jason Leigh, Eds. 2008, The Eurographics Association.

[120] Harold Mytum and John R. Peterson, "The Application of Reflectance Transformation Imaging (RTI) in Historical Archaeology", *Historical Archaeology*, vol. 52, no. 2, pp. 489–503, Jun 2018.
URL: *https://doi.org/10.1007/s41636-018-0107-x*

[121] Tobias Isenberg, Bert Freudenberg, Nick Halper, Stefan Schlechtweg, and Thomas Strothotte, "A Developer's Guide to Silhouette Algorithms for Polygonal Models", *IEEE Computer Graphics and Applications*, vol. 23, no. 4, pp. 28–37, 2003.

[122] Penley Knipe, "Paper Profiles: American Portrait Silhouettes", *Journal of the American Institute for Conservation*, vol. 41, no. 3, pp. 203–223, 2002.

[123] "Lavater's Apparatus for taking Silhouettes", *Scientific American*, vol. 41, no. 16, pp. 249, 1881.

[124] Farzin Mokhtarian, "Silhouette-based Occluded Object Recognition through Curvature Scale Space", *Machine Vision and Applications*, vol. 10, no. 3, pp. 87–97, 1997.
URL: *https://doi.org/10.1007/s001380050062*

[125] Amy Gooch, Bruce Gooch, Peter Shirley, and Elaine Cohen, "A Non-Photorealistic Lighting Model for Automatic Technical Illustration", in *Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques*, New York, NY, USA, 1998, SIGGRAPH 98, p. 447452, Association for Computing Machinery.
URL: *https://doi.org/10.1145/280814.280950*

[126] Adrian Bowyer, "Computing Dirichlet tessellations", *The Computer Journal*, vol. 24, no. 2, pp. 162–166, Jan. 1981.
URL: *https://doi.org/10.1093/comjnl/24.2.162*

[127] D. F. Watson, "Computing the n-Dimensional Delaunay Tesselation with Application to Voronoi Polytopes", *The Computer Journal*, vol. 24, no. 2, pp. 167–172, 1 1981.
URL: *https://doi.org/10.1093/comjnl/24.2.167*

[128] Francesco Dell'Accio and Filomena Di Tommaso, "Scattered data interpolation by Shepard's like methods: Classical results and recent advances", *Dolomites Research Notes on Approximation*, vol. 9, pp. 32–44, Oct. 2016.
URL: *http://drna.padovauniversitypress.it/2016/specialissue/5*

[129] Panagiotis Theologou, Ioannis Pratikakis, and Theoharis Theoharis, "A comprehensive overview of methodologies and performance evaluation frameworks in 3D mesh segmentation", *Computer Vision and Image Understanding*, vol. 135, pp. 49–82, Jun. 2015.
URL: *https://linkinghub.elsevier.com/retrieve/pii/S1077314215000028*

[130] Anna Maria Manferdini and Fabio Remondino, "Reality-Based 3D Modeling, Segmentation and Web-Based Visualization", in *Digital Heritage*, Marinos Ioannides, Dieter Fellner, Andreas Georgopoulos, and Diofantos G. Hadjimitsis, Eds., Berlin, Heidelberg, 2010, pp. 110–124, Springer Berlin Heidelberg.

[131] Eleonora Grilli, D. Dininno, Giulio Petrucci, and Fabio Remondino, "From 2D to 3D supervised segmentation and classification for cultural heritage applications", *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-2, pp. 399–406, 2018.
URL: *https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2/399/2018/*

[132] Will Schroeder, Ken Martin, and Bill Lorensen, *The Visualization Toolkit - An Object-Oriented Approach to 3D Graphics*, Kitware Inc., 4.1 edition, 2018.

[133] Manuela Martins, "Projeto de *Bracara Augusta*. 38 Anos de Descoberta e Estudo de uma Cidade Romana.", *Revista da Faculdade de Letras-Ciências e Técnicas do Património*, vol. 13, pp. 159–169, 2014.

[134] Luis Fontes and Mafalda Alves, "O Parque Arqueológico do Vale do Terva. Um Projeto de Paisagem Cultural", in *Paisagens Mineiras Antigas na Europa Ocidental. Investigação e Valorização Cultural*, Luis Fontes and Mafalda Alves, Eds., Boticas, Portugal, July 2014, pp. 113–142.

[135] Paulo Bernardes and Manuela Martins, "Computer Graphics and Urban Archaeology: *Bracara Augusta*'s case study", *Portuguese Journal of Computer Graphics - Special Edition of Virtual Journal: Advances of Computer Graphics in Portugal*, Nov. 2004.

[136] Fernanda Magalhães, "Espaço Doméstico e Sociabilidades: as Domus de Bracara Augusta", in *Cotidiano e Sociabilidades no Império Romano*. 2015.

[137] Fernanda Magalhães, Jorge Ribeiro, and Manuela Martins, "Entre o Público e o Privado. Cenários do Quotidiano na *Domus* das Carvalheiras", *Romanitas Revista de Estudos Grecolatinos*, vol. 6, pp. 88–106, 2015.

[138] José Rui Coelho da Silva, "A insula das Carvalheiras. Estudo de um exemplo de arquitectura privada em *Bracara Augusta*,", Master's thesis, Universidade do Minho, 2000.

[139] Manuela Martins, "Entre o Ócio e a Sociabilidade: o Papel das Termas Públicas na Vida Social de Bracara Augusta", in *Cotidiano e Sociabilidades no Império Romano.* 2015.

[140] Manuela Martins, *As termas romanas do Alto da Cividade. Um exemplo de arquitectura pública de* Bracara Augusta, vol. I, Braga, Bracara Augusta. Escavações Arqueológicas edition, 2005.

[141] Manuela Martins and Maria do Carmo Franco Ribeiro, "Gestão e Uso da Água em Bracara Augusta : uma Abordagem Preliminar", in *Caminhos da Água – Paisagens e usos na longa duração.* 2012.

[142] Ana Garrido Elena, Ricardo Mar, and Manuela Martins, *A Fonte do Ídolo. Análise Interpretação e Reconstituição do Santuário*, Unidade de Arqueologia da Universidade do Minho, Braga, 2008.

[143] Lara Bacelar Alves and Mário Reis, "No limiar das artes? - Questões em Torno da permeabilidade de Fronteiras Temporais e Espaciais da Arte Rupestre de Trás-os-Montes Ocidental", vol. 41, pp. 45–92, 2009.
URL: *https://goo.gl/pXaJrq*

[144] Luís Fontes, Bruno Osório, Mafalda Alves, and Maurício Guerreiro, *Atlas da Arqueologia do Parque Arqueológico do Vale do Terva*, Unidade de Arqueologia da Universidade do Minho, Boticas, 2017.

[145] Luís Fontes, Bruno Osório, and Mafalda Alves, "Povoamento e Paisagens no Vale Superior do Rio Terva, Boticas. Projeto de Investigação Plurianual em Arqueologia (PoPaTERVA 2013-2016). Trabalhos Arqueológicos no Castro de Sapelos. Relatório 2014", Tech. Rep., Unidade de Arqueologia da Universidade do Minho, 2015.

[146] Bruno M.S.C. Martins, *A Depressão de Régua-Chaves-Verin. Contributo para a Análise do Risco de Ravinamento.*, PhD thesis, Universidade de Coimbra, 2009.

[147] Bruno Pereira and João Azevedo, "Prospeção Geofísica e Modelação Tridimensional do Castro de Sapelos. Relatório Final", Tech. Rep., Sinergeo, Soluções Aplicadas em Geologia, Hidrogeologia e Ambiente, Lda., Braga, 2014.

[148] David B. Arnold, Alan Chalmers, and Franco Niccolucci, Eds., *Proceedings of VAST 2003: The 4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, Brighton, United Kingdom, Nov. 2003. Eurographics Association.