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ENHANCED CULTURAL EXPERIENCE BASED ON SMART USE OF 3D DIGITIZED CULTURAL HERITAGE ARTIFACTS

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ABSTRACT

Three-dimensional (3D) digitization has been intensively applied to cultural heritage (CH) assets during the past two decades. Because of the advancements in 3D tools and technologies, the massive digitization of CH assets is becoming common in museum practices. 3D digitized CH collections can be used with different narration levels through various 3D technologies such as augmented reality (AR), virtual reality (VR), 3D printing, and digital screen displays.

Despite the versatility of 3D digitization projects, they are currently not adequately focused on end-user experience. The massive 3D digitization is still not reaching the fundamental goals of CH valorization, preservation, and promotion. Museums are not solely interested in digitizing their collections to create repositories of replicas, but they are also eager to use these technologies to promote and raise public awareness about the treasures housed in their collections. Therefore, digitization projects should be more directed toward goals such as (i) attracting visitors to the museum to view the physical CH assets and not just to see their virtual replicas online; (ii) preserving the diversity of values that can be attributed to heritage, which does not solely rely on its materials and appearance but also on the integrity of all its components, its intangible qualities, and the narratives attached to it; (iii) assisting specialists of different fields working with CH objects by merging interdisciplinary data on one platform. However, currently, most literature on 3D technologies for CH focus on either the technical aspects or how to enhance the quality to achieve the most realistic aspect.

The information stored in massively 3D digitized CH collections is currently disconnected from their usage, both for the specialists (museum professionals, restorers, researchers, and technicians) and the museum visitors. On the one hand, the massive 3D digitization of the cultural heritage assets represents several challenges in process optimization to create high-quality digital models while working in difficult situations. On the other hand, its practical use for CH valorization, and to design narratives and cultural experiences is lacking in most existing practices.

The lack of theoretical foundations before developing and implementing any technology can create problems such as misalignment between different researchers and professionals, slowing down the innovation process, and resulting in a less efficient design of an experience. The attempts made in the past in interactive museum visits made it clear that relying only on the intuition of designers for implementing technologies in a museum can be risky. Analytical tools are needed to foster a more systematic and reflective approach to the design, implementation, and deployment of technology in museums.

To deal with these challenges, the interdisciplinary research presented in this thesis aims to evaluate the use of digitized museum artifacts in significant contexts of designing cultural experiences and narratives. The results of this research are a step toward creating a comprehensive framework using quantitative and qualitative research approaches to evaluate best practices in the digitization of CH and its applicability to museum education, museum presentation, CH valorization, research, conservation, and restoration. The proposed framework evaluates the design of user experience with different modes of interaction between people and cultural assets by studying the perception of art. It also incorporates guidelines to efficiently perform 3D digitization of CH assets for designing user experience and interaction.

In this research different guidelines and evaluation criteria for an enhanced museum experience were theorized by applying empirical mixed methods research. The interdisciplinary methods and techniques employed in this research evaluate experience design for the use of data that are

not easily narratable by traditional methods. The proposed theratical framework suggests various aspects of cultural experience through digital interactions with CH assets and provides possible design choices for such aspects. It is intended to be employed by CH professionals, designers, digital application developers, and researchers to support their decision-making about important criteria for the design, development, and implementation of interactive systems. It will also enable designers and museum professionals to create new forms of exhibition, visitors' engagement, and museum learning.

The research explicitly investigates different modes offered by 3D technologies to merge visual content with varying types of information for designing cultural experiences and creating narratives. The framework proposed in this research aims to evaluate the design of cultural experience to enrich and differentiate the museum visits and assist the professionals in their daily practices. It evaluates the effectiveness of employing 3D technologies to connect narratives with digital models for creating better experiences for museum visitors, researchers, and CH professionals. 3D digitization of museum contents, which has recently become a common practice for complete museum collections, provides the possibility to test the theoretical results of this research in real scenarios.

By combining the disciplines of 3D digitization and museum experience design, the resulted framework could be applied for the improved uses of digitized CH in a way that is comprehensible and attractive because of its meticulous nature and emotional aspects. Instead of only focusing on the modality of content delivery to the audiences, this research evaluates new forms of communication languages for researchers and CH professionals. Thus, this research is not only an evaluation of technological applications for museum visitors but also provides solutions for the exhibition design, museum curation, and CH research. By employing the technology for museum experience design and interactive narrative creation, the research will enable cultural institutions to connect with their audiences, bring together different audiences, attract new visitors, enhance visitors' CH experience, and create new insights into the cultural stories.

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1. INTRODUCTION AND FRAMING OF RESEARCH

In recent years, three-dimensional (3D) technologies have been adopted in many fields, including Cultural Heritage (CH). Because of the advancements in 3D technology, the massive digitization of CH assets is becoming a common practice in museums. The whole museum collections are being digitized in 3D and are being stored with linked metadata and annotations on the surface of 3D models. [1] Several types of data components can be associated with an entire object or a segment by using annotations over 3D models. For 3D models of CH assets, the annotated data components could be related to the restorations, defects, historical interpretations, reconstruction of the original appearance, etc. Currently, 3D digital CH collections contain both the information related to the visualization of CH assets (the digitized representation of CH assets) and the data components associated with them. Such information can be used for:

- digital archiving
- to create high fidelity physical replicas of artworks
- digital restoration
- monitoring of endangered CH
- to trigger the general public interest in cultural heritage by making digitized content available through the internet
- to study cultural heritage assets for research purposes in a way that is usually not possible with physical objects

For all of these purposes, 3D digitized CH collections can be presented with different narration levels through various 3D technologies such as augmented reality (AR), virtual reality (VR), 3D printing, and digital screen displays.

The opportunities offered by 3D technologies have become a topic of interest in the fields of CH and museum practice. Disasters such as the fire in the Notre Dame cathedral in Paris (2019) and the Islamic State's destruction of archaeological sites, notably in Palmyra (2015-16), highlight the fragility of our heritage. It is precisely here that technology can offer ways of reviving and preserving the material qualities of artifacts, works of art made of fragile materials, and objects in museum collections [De Luca 2020; Denker 2017]. Over the years, 3D digitized and 3D printed models of CH objects have been created during the restoration and reconstruction of works of art. Not only are these technologies promising for the conservation and preservation of our heritage, but it has also become apparent that engaging with and researching works of art today without the help of 3D digitization is less and less common. The facility with which artworks can be used, adjusted and distributed via these technologies promotes much greater accessibility and stimulates a richer array of experiences than would have been possible in a traditional museum setting. Similarly, to carry out the fundamental educational role of museums [Hooper-Greenhill 1999], the use of digital and physical replicas has been widely recognized in the scientific literature [CECA 2014; Freeman et al. 2016; Antonaci et al. 2013; Fatta et al. 2018].

[1] Annotation of 3D models is a mechanism that links a specific location/region on the surface of the geometrical representation of an object to some related information.

The information stored in 3D digitized CH collections is currently disconnected from their usage via digital technologies, both for the specialists (museum professionals, restorers, researchers, and technicians) and the general public. On the one hand, the massive 3D digitization of the cultural heritage assets represents several challenges in terms of process optimization to create high-quality digital models in less time while working in difficult situations. On the other hand, its effective use in terms of experience and perception of the end-users (researchers, museum professionals, and museum visitors) is lacking in most of the existing practices.

To deal with these challenges, this interdisciplinary research aims to efficiently digitize museum artifacts to be used in the most significant contexts of cultural experience. The results of this research are a step towards creating a comprehensive framework, by using both quantitative and qualitative research approaches, for evaluation of best practices in 3D digitization of CH and its applicability to museum education, museum presentation, research, conservation, and restoration. The proposed framework evaluates user experience with different modes of interaction between people and cultural assets by studying the perception of art when presented through various 3D technologies. It also incorporates guidelines to efficiently perform 3D digitization of CH assets for requirements of experience and interaction.

1.1 Structure of the thesis

This research is composed of five components (Figure 1.1.). It started with desk research by defining the methodology and reviewing the existing practices and uses of 3D digitization based on the literature review. Concurrently, several guidelines and best practices for optimizing the 3D digitization process were established in the lab research based on lessons learned from the best practices in 3D digitization projects developed during this research. The same projects were also used for evaluating the user experience with 3D digitized CH artifacts through field studies. The field research included: interviews with scholars, a workshop with all the stakeholders of the research, questionnaires, and interviews with museum visitors. The final part is the compilation of results in form of a framework.

The structure of this thesis largely follows the sequence of the same four components represented in figure 1.1. The current chapter introduces the problem and defines the research questions by positioning this study among the related scientific fields. This chapter also defines the research methodology.

Chapter 2 is a brief analysis of the past works and best practices in various related fields based on a literature review.

Chapter 3 focuses on a brief explanation of four projects developed simultaneously with this research. The projects presented in this chapter made use of 3D models of various forms of CH assets with different objectives in each case. The forms of CH assets utilized in these projects included sculptures, paintings, monuments, and other museum objects. The objectives of these projects included education, museum presentation, research, and conservation. It was opportune to explain these projects before starting the discussion about the effectiveness of 3D digitization for the enhanced cultural experience, as different modes of interactions with 3D digitized cultural heritage were proposed in these projects.

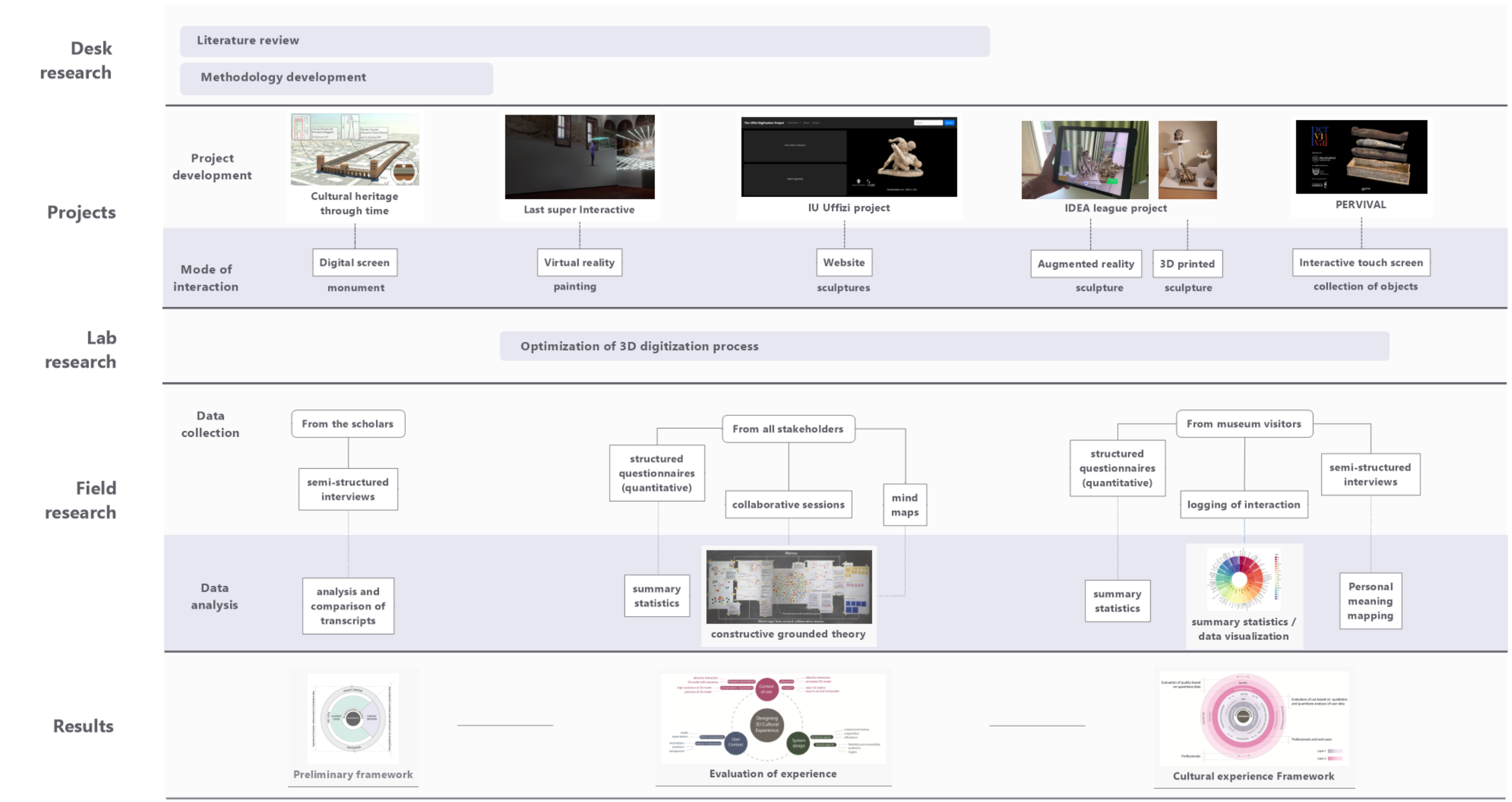


Figure 1.1. The five components of this research.

Before starting the discussion about the effectiveness of 3D digitization for enhanced cultural experiences, chapter 4 identifies best practices for effective 3D digitization of CH assets in museums. It also provides the metrological guidelines for the optimal accuracy of reality-based 3D models. The resulting material can then be converted to create interactions between users and CH assets for different experiences such as those demonstrated through the practical projects in chapter 3. Parts of the contents of this chapter are the subject of two published articles [Malik and Guidi 2018; Guidi et al. 2020a]. The test case, for optimizing the 3D digitization process in museum environments, is the massive 3D digitization project of the Uffizi Gallery in Florence, Italy. This project is among the projects discussed in chapter 3. The metrological guidelines related to optimal overlap between consecutive images in automatic photogrammetry are provided based on laboratory tests.

Although quantitative research methods are considered reliable for many engineering problems such as those presented in chapter 4, many complex social aspects in experience design cannot be evaluated only quantitatively. Therefore, the question of cultural experience with 3D digitization was approached by using mixed methods research. Chapter 5 explains the protocols and procedures adopted to collect both qualitative and quantitative data from the stakeholders of this research: (i) Researchers / Scholars; (ii) Art historians / Archeologists / Museum professionals; (iii) Designers; (iv) Engineers / Digital application developers and (v) Museum visitors. Using the projects presented in chapter 3 as case studies, both qualitative data (interviews, questionnaires, formal conversations, and a workshop) and quantitative data (questionnaires and application logs) were collected from the stakeholders in this chapter. Evaluation of such data provided some criteria for the enhanced cultural experience which were later integrated into a framework (outcome of this research). Part of the contents of this chapter is the subject of a published article [Malik et al. 2021].

Chapter 6 combines the evaluations of qualitative data from chapter 5 and quantitative guidelines for improved efficiency of the 3D digitization process reported in chapter 4. At this point, all the evaluation criteria and guidelines are brought together in form of a theoretical framework. This chapter delineates different aspects of the framework and provides directions on how to navigate through it. The chapter also simulates the functionality of the proposed framework by applying it to two different projects.

Chapter 7 starts by summarizing the results and a discussion about the contributions. This chapter also examines the impacts of this research both on the academic and institutional levels. Finally, the shortcomings of this research are reviewed and future research directions are suggested.

1.2 Research motivations and objectives

The motivation for conducting this research is to improve the quality of the massive digitization of CH assets and link it to the usage phase for different stakeholders to enhance cultural experiences both inside and outside of the museums.

1.2.1 Disconnection between 3D digitization and CH preservation/promotion goals

Over the last decade, three-dimensional technologies have conquered many fields. 3D digitization offers the possibility to reproduce nearly any object no matter its size, material, and shape. It is becoming a common practice to digitize the museum contents. Reality-based 3D digitization has been extensively used for digital reconstructions of Cultural Heritage (CH). Starting from the early international experiences [Levoy et al. 2000; Godin et al. 2002; Guidi et al. 2004b], developments in digital photography and automatization of algorithms for features extraction from images [Lowe 1999; Lowe 2004; Yan Ke and Sukthankar 2004; Bay et al. 2006] led to a new role of image-based 3D modeling in several areas including CH documentation [Pieraccini et al. 2001; Guidi et al. 2009a]. Based on these developments, several museums started to experiment with 3D digitization of a limited set of objects [Bernardini et al. 2002; Levoy 1999; Atzeni et al. 2001; Bryce 2015]. Following these projects, a few large-scale initiatives for 3D digitization of collections of archeological artifacts were started worldwide: the European project 3DICONS [Guidi et al. 2013], the UCL's Petrie Museum of Egyptian Archaeology [Robson et al. 2012], and the Smithsonian 3D digitization, to name a few. More recently, the Uffizi Gallery in Florence started three-dimensional digitization of its complete collection of sculptural heritage [Guidi et al. 2018].

Despite the usefulness of 3D digitization projects, they are currently not properly focused on end-user experiences for different purposes. The massive 3D digitization is still not reaching the real goals of CH (both physical and digital) preservation and promotion according to the principles defined by several international organizations [CECA 2014; CIDOC 2012; ICOMOS 2003; ICOMOS 2008; UNESCO 2009].

The International Council of Museums (ICOM) [ICOM 2021] defines a museum as "a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment." Therefore, museums are not solely interested in digitizing their collections to create repositories of digital replicas, but they are also eager to use these technologies to promote and raise public awareness about the treasures housed in their collections. Therefore, digitization projects should be more directed toward goals such as (1) attracting visitors to the museum to view the physical CH assets and not just to see their virtual replicas online; (2) preserving the diversity of values that can be attributed to heritage [Szmelter 2013], which does not solely rely on its materials and appearance but also on the integrity of all its components and its intangible qualities [Carboni and De Luca 2016]; (3) assisting specialists of different fields working with CH objects by merging interdisciplinary data on one platform. However, most of the literature about these 3D technologies for CH focus on either the technical aspects or how the quality of the digitization can be altered to achieve perfection [Remondino 2011; Balletti et al. 2018].

1.2.2 Significant contexts of utilizing 3D digitization for cultural experiences

Recently, in CH research, "the digital" and the digitization of CH have started to become the new norm. This concept has been defined in the context of the post-digital museum [Parry 2013a]. The consequences of the introduction of post-digital media on museum studies have been largely studied within the fields of museum experience design and visitor experience [Mason 2020]. Although these studies have contributed to revealing the importance of 3D digitization in contemporary museum research, the specific applications of 3D digitization, its implementation, and perception have not been investigated thoroughly. The role of 3D digitization and its possible usefulness in conservation and museum studies is often ignored, and the possible consequences for museums are unexplored. Important theorists within museum discourse such as [Hooper-Greenhill 2013; Dudley 2013; McClellan 2008; Macdonald et al. 2015] rarely if ever write about the role of digitization in material, visual and living culture. Although the digitization of art is more often treated in conservation studies than it is in museum studies, the literature is still scarce

[Viñas 2002; Scott 2016] and work published to date does not consider more contemporary 3D technologies (AR, VR, 3D printing) concerning restoration and conservation.

By using 3D digitized models or physical replicas of CH with several layers of narratives, museums can engage more audiences by providing additional levels of experience in **museum presentation**. Museums can create different levels of immersivity to show geometrical and visual aspects of an object linked to additional layers of narratives. The presentation could be as simple as a 3D viewer on a digital screen to more complex augmented and immersive experiences in a digital world. Starting from the classical museum experience model [Dierking and Falk 1992], the literature suggests the importance of new ways afforded by digital technology to interact with visitors [Vermeeren et al. 2018; Freeman et al. 2016]. Recently, there has been an increase in studies that analyze the possibilities of 3D technologies for experiences in museums, but most of these studies remain focused on studying a single aspect of the experience. Some of the examples include personalization of visitor experience by user modeling and context analysis [Ardissono et al. 2012], use of touchable physical replicas in museums for diverse audiences (people with learning difficulties, children, elderly, blind or visually impaired visitors), [Balletti et al. 2018; Neumüller et al. 2014; Wilson et al. 2017] use of 3D reconstructions for interactive museum experiences (both tangible and intangible components of heritage) [Petrelli et al. 2014; Duranti et al. 2016; Petrelli 2019], and co-designing in museums with 3D technology [Ciolfi et al. 2015].

The educational role of museums is the fundamental and long understood objective of the museums. The massive museum digitization in the 21st century has brought new and innovative ways of museum education. Modern museums have adopted the "dialogue approach" for visitors' participation and creative engagement [McLean 1999]. Digital technologies have been tested and implemented for **museum education** in many contexts. The influence of digital technologies is often discussed in publications on museum learning and education [Menano et al. 2019; Liguori and Rappoport 2018; Alexandri and Tzanavara 2014]. The M3 learning model [Vavoula and Sharples 2009] evaluates the mobile technologies in terms of learning in museums during the early stages of their development, during the implementation, and their long-lasting effects. This model can also be applied to improve the digital literacy of the CH professionals, as being explored in the recent British project "One by One" [Barnes et al. 2018]. Yet, the importance of digital technologies in museums is highlighted in these studies without specifically focusing on the 3D technologies and reproductions of CH objects.

The activities related to **CH conservation and restoration** are traditionally bound to the manual skills of the professional. With the introduction of digital technologies in the CH profession, the field of conservation/restoration has also seen a shift toward interdisciplinarity, and the role of 3D models in facilitating the activities of CH professionals has become essential. The periodic 3D shape and surface evaluations of the shape of CH artifacts, structures, or sites can reveal degradations and defects not visible to the naked eye. Some examples of CH monitoring for conservation include high-resolution 3D monitoring of deformations in wooden artworks [Guidi et al. 2007], multi-temporal monitoring of built heritage continuously exposed to risks and hazards [Abate 2019], the impact of restoration on panel painting [Palma et al. 2019], and conservation and decay mapping of stone heritage [Salonia et al. 2011; Meneely et al. 2009]. Apart from the use of 3D models for documentation and monitoring in heritage conservation, the digital counterparts of CH artifacts allow modifications and integrations of missing parts according to the rules of restoration without physically touching the original object [Frischer 2014]. 3D models can be used as research tools for the execution of specific investigations and as a supporting media for the archival and integration of all the restoration-related information [Scopigno et al. 2003]. In a recent review publication, [Acke et al. 2021] listed different scenarios of using 3D models for the conservation and restoration of CH. A positive trend toward 3D technologies in restoration projects was demonstrated based on the survey carried out in this publication. Yet, the same publication outlines several issues requiring considerations for fully incorporating the 3D technologies into the restoration practices. Such issues include the production process and materials of physical replicas, necessary technical knowledge of the professionals, the applicability, ethical considerations, time and cost of implementation, and management of the stored and archived data.

The literature suggests the importance of digital technology to interact with users for different purposes highlighted above. There has been an increase in studies to analyze the possibilities offered by 3D technologies for experiences in museums and CH research, but most of these studies remain focused on studying only one aspect of cultural experience. Furthermore, within the studies that do focus on different aspects of CH experience with 3D technologies, there still is a division between digital versus physical methods of interactive experiences [Di Giuseppantonio Di Franco et al. 2018; Neumüller et al. 2014; Lowe 2020]. Studies that do analyze multiple 3D technologies are mainly invested in establishing the "dos and don'ts" of experimenting with a 3D technology, studying technical limits, and often do not offer a deep investigation of the impact these technologies have on our perception of art or on the sense of authenticity, or "aura," we experience when interacting with art [Callet 2014].

Recent publications fail to treat the significance of 3D technologies for restoration, conservation, participation, education, art history, and the authentic experience. No single comprehensive study has yet been executed that examines and compares the use of different 3D technologies for various purposes as well as the implications of these technologies on the experience of CH assets.

1.2.3 Specific objectives and beneficiaries of the research

With the advancement in 3D digitization, the vast availability of interactive 3D technologies, and the leniency of museums towards the adoption of technology, 3D interactive exhibitions are becoming a common practice as a part of the museum visit. 3D models of CH assets have also been extensively used by researchers and CH professionals for their professional needs. However, the research in 3D digitization has so far focused on the development and evaluation of new systems while more theoretical and conceptual research on the usage and experience with 3D digitization is still lacking.

The lack of theoretical foundations before developing and implementing any technology can create problems such as misalignment between different researchers and professionals, slowing down the process of innovation, and resulting in a less efficient design of the experience. The attempts made in the past in interactive museum visits made it clear that relying only on designers' intuition for implementing technologies in the museum can be risky. There is a need for analytical tools fostering a more systematic and reflective approach to the design, implementation, and deployment of technology in museums [Kaptelinin 2011].

The framework proposed in this research aims to evaluate innovative ways of cultural experience to enrich and differentiate the museum visits and to assist the professionals in their daily practices. The research specifically investigates different modes offered by 3D technologies to merge visual content with different types of information: for the content (technical, historical, artistic information…) and the representation (3D, 2D, text, audio…). The interdisciplinary methods and techniques employed in this research evaluate:

- 3D digital experience design for the use of data that are not easily "narratable" by traditional techniques
- user interaction with the applications utilizing 3D digitized CH assets
- visualizations with information components used in 3D technologies
- 3D acquisition of assets for implementing the 3D applications, with photogrammetric techniques and laser scanning
- information systems connected to the CH assets using the 3D models as an access portal
- digital curation using 3D media

The theoretical framework produced in this research will provide designers, developers, and CH professionals with the means to guide a sensible design of interactive 3D experiences, by exploiting the potentialities offered by 3D technologies with clear methods to achieve them. It evaluates the effectiveness of using the 3D digitized CH assets and employing 3D technologies as tools to connect narratives with digital models for creating better experiences for museum visitors, researchers, and CH professionals. 3D digitization of museum contents, which has recently become a common practice for complete museum collections, provides the possibility to test the theoretical results of this research in real scenarios.

By combining the two disciplines of 3D digitization and technology-enhanced museum experience, the expected result will be the improved uses of digitized CH in a way that is comprehensible and attractive because of its meticulous nature and emotional aspects. A combination of the technology with museum experience and interactive narrative creation proposed in this research will enable cultural institutions to connect with the audience to:

- bring together different audiences
- attract new visitors
- enhanced cultural heritage experience for the visitors
- create new insights into the cultural stories

Additionally, along with optimizing the technology for museum experience, the research focuses on exploring the possible modalities of using the digitized CH assets for researchers and CH professionals. Instead of only focusing on the modality of content delivery to the audiences, the framework evaluates new forms of exhibition and communication languages for researchers and CH professionals. Thus the research is not only an evaluation of technological applications for museum visitors but also provides solutions for the exhibition design, museum curation, and CH research.

1.3 Research positioning and research questions

In this digital era, the CH research has moved from manual traditional methods to more computerized digital methods and the museums are no longer dependent only on the traditional communication tools such as panels to engage with their audiences. Museums are proposing more and more digital interactions to enrich visitors' experiences, develop interest, and attract new audiences. Furthermore, in the fields of conservation and restoration of cultural heritage assets, there is a constant need for higher quality records and better analytical tools for extracting information about the condition of artifacts [MacDonald 2006]. Digital technologies provide these capabilities, and technological advances in digitization have enabled professionals and researchers to create high-quality repositories and assessment tools.

It is clear that the CH practices and museum studies have taken a "digital turn". The UNESCO Charter on the Preservation of Digital Heritage defines this turn as a new field of study—the digital heritage: "resources of information and creative expression are increasingly produced, distributed, accessed and maintained in digital form, creating a new legacy—the digital heritage. [UNESCO 2009]". As a result, digital technology has been largely unmapped in terms of a critical theory for cultural heritage and heritage institutions [Cameron and Kenderdine 2007].

According to the European Commission's recent Horizon Europe Work Program 2021-2022, the use of digital and cutting-edge technologies is of fundamental importance for protecting, preserving, and enhancing cultural heritage and scale-up the competitiveness of cultural and creative industries [European Commission 2021]. According to this program during the next 10 years, the research and innovation activities will be oriented toward interdisciplinary research and will actively involve the cultural, technical, and creative industries through broad cooperation of a wide set of stakeholders and efficient coordination between them. Aligned to these goals, this research is dealing with the application of 3D digitization for different purposes with an aim of evaluating it at the application phase by involving various stakeholders. Therefore, digital heritage, as a field of study, is at the heart of this research. "Museum experience design" for evaluating the experiences of the stakeholders and "Reverse Engineering/Computer Vision" for content generation and quality control are the interdisciplinary disciplines linked to the core of this research (Figure 1.2).

The area of reverse engineering through computer vision deals with acquiring the geometry and appearances of an object and reconstructing its digital model without the aid of drawings, documentation, or a computer model [Varady et al. 1997]. This method has been vastly adopted in many fields such as industrial design, mechanical engineering, medical industry, and architecture. The developments in reverse engineering have broadened its applications also in the field of cultural heritage for preservation, reproduction, maintenance, monitoring, education, and dissemination. The traditional work of CH professionals, archaeologists, and art historians has been gradually transformed due to the development of three-dimensional reverse modeling techniques. Virtual 3D models of CH objects and sites have become common tools for analyses, testing hypotheses, and creating research repositories. The 3D digital tools make CH accessible to a wider public and represent an invaluable means for education and dissemination by creating public interest.

Besides digitizing their collections, the museums and cultural heritage institutions are interested to involve the public at various levels. Therefore, the disciple of museum experience design has been included in this research. It studies the use of digital technologies by analyzing their strengths and weaknesses in terms of both methods and applications. This area also investigates the impact of interactive digital installations on visitors' experience and perception of artworks. A wide range of areas such as interaction design, user experience design, visitor studies, and museology are covered under the umbrella of this discipline.

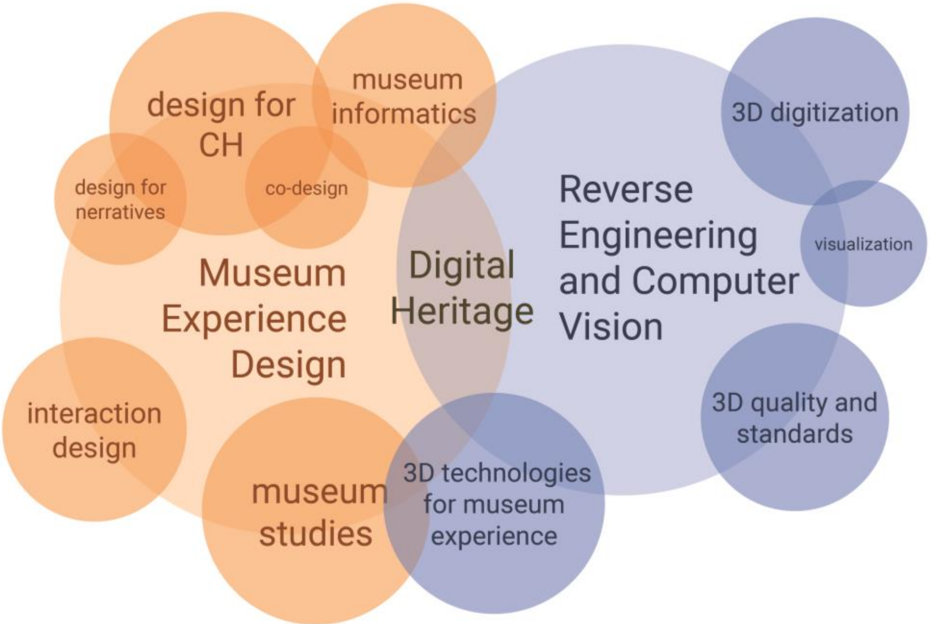


Figure 1.2: Two disciplines of this research. The research focus is at the intersection and research questions were subtracted from involved areas of research.

Research questions were individualized from each discipline involved in this research. This research represents an attempt to answer the following questions:

3D digitization for enhanced cultural experiences

i. In what way 3D technologies with digitized collections can contribute to the experience of CH objects for museum education, CH research, conservation/restoration, and museum presentation?

Best practices for 3D digitization of museum collections

ii. What are the challenges and best practices for the 3D digitization of large museum collections in a short time?

User interaction and perception of 3D digitized CH assets

iii. What are the factors to be considered to design enhanced experiences and interactions with 3D digitized CH assets?

iv. How are 3D technologies perceived by different stakeholders (researchers, museum professionals, and museum visitors)?

1.4 Methodology

As a response to the polarization between quantitative and qualitative research, a new intellectual movement of methods occurred at the end of the 20th century. This movement, combining different research methods, has been given many names such as blended research, integrative research, triangulated studies, ethnographic residual analysis, multimethod research, and mixed research. An advantage of using a broader term such as "mixed research" or "multimethod research" is that it does not suggest a limitation of mixing the methods only. Mixed methods research is defined as "the research methodology in which the researcher collects, analyzes, and mixes (integrates or connects) both quantitative and qualitative data in a single study or a multiphase program of inquiry [Creswell and Clark 2017]." Other methodologists use the term "multimethod research" to suggest that different styles of research may be combined in the same research project. These research methods do not require to be restricted to quantitative and qualitative, but may include qualitative participant observation with qualitative in-depth interviewing and quantitative survey research with quantitative experimental research [Hunter and Brewer 2002]. The mixed methods research was adopted from the early times of its origination because of the following advantages stated by [Jick 1979]:

- it allows researchers to be more confident in their results
- it stimulates the development of creative ways of collecting data
- it can lead to thicker, richer data
- it can lead to the synthesis or integration of theories
- it can uncover contradictions
- by virtue of its comprehensiveness, it may serve as the litmus test for competing theories

In this research, instead of giving a definite answer to the problem, the methodology to answer the research questions has been made open to more critical analysis and explanation of the phenomenon. In other words, this research is not "solution-oriented", but rather "model-oriented". The output of the research is not a definite solution but a framework for the solutions for the cultural experience. To realize a framework with comprehensive data, this research is a proper mix of quantitative and qualitative techniques (mixed methods research). Due to its interdisciplinary nature, different methods of data collection and analyses were required at different stages of this research. Mixed methods research provides such freedom to combine different methods, hence it was the most suitable choice. The specific research tools and evaluation methodologies for this mixed methods research include:

- Open-ended questionnaires, semi-structured interviews [Galletta 2013; Kvale 2008], ethnographic observations, and focus groups for qualitative data collection
- Lab experiments, structured questionnaires, and user interaction logging for quantitative data collection
- Constructive grounded theory [Charmaz 2006; Corbin and Strauss 1990], personal meaning mapping [Falk and Dierking 2003], and content analysis [Mayring 2015] for qualitative data analysis
- Summary statistics for the quantitative data analysis.

The quantitative methods were used to create guidelines for the best quality of 3D digitization of CH assets, while for the experience evaluation both quantitative and qualitative methods were used. Through these tools and methods, different projects (chapter 3) were analyzed by involving all the stakeholders of this research in the process. Such projects utilized different types of 3D digitized CH assets (sculptures, paintings, museum objects, monuments) for different purposes (museum education, CH research, conservation/restoration, and museum presentation).

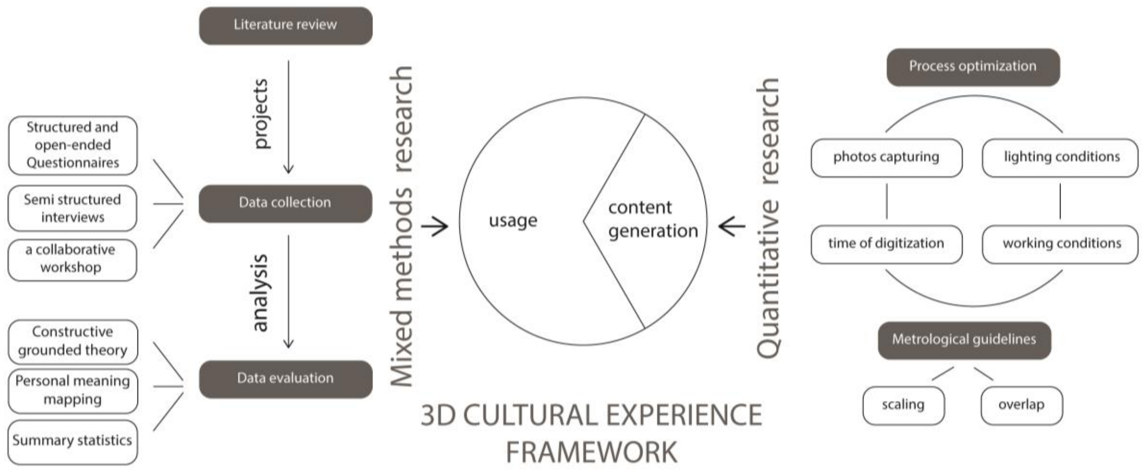


Figure 1.3: The research tools and methods implemented in this research.

The research started by reviewing the existing practices and uses of 3D digitization based on the literature review and recent projects. Secondly, grounded in best practices and laboratory experiments, guidelines for optimizing the 3D digitization process were created. Later, the 3D technologies were evaluated for enhanced cultural experience by using mixed methods research and engaging with the stakeholders of this research. Towards the end, both guidelines for optimizing the digitization process and the evaluation criteria for experience were integrated into a framework (Figure 1.3).

The first step of this research is a systematic literature review (chapter 2) to point out the gaps and to compare the effectiveness of different forms of interaction between a user and a CH asset through 3D technologies. The progress and gaps in two main aspects of this research (3D digitization of museum contents and museum experience design) were investigated at this step.

The second step of this research is to create guidelines based on best practices in the 3D digitization of CH assets in museums and for making the resulting material suitable for different experiences that can be achieved by such digitized models. The test case, for optimizing the 3D digitization process in museum environments, was the massive 3D digitization project of the Uffizi Gallery in Florence, Italy. Related to the methodological approaches adopted for improved efficiency and to deal with the metrological challenges, this research has produced serval guidelines for carrying out massive 3D digitization of museum contents [Malik and Guidi 2018; Guidi et al. 2018; Guidi et al. 2020a]. At the same time, the 3D digitized models that are the bases of this research have also been made public alongside their metadata and paradata.

In the third step of this research, a mixed-methods approach was used by collecting both quantitative and qualitative data on user experience. For this part, several activities were performed including interviews, questionnaires, quantitative logging of interaction, and a collaborative workshop. These activities started by interviewing prominent scholars in the fields related to digital heritage (chapter 5). The analyses of interviews with the scholars compared with the reviews of the literature were used to develop the preliminary framework for this research. Subsequently, several projects were used as starting point of discussion with all the stakeholders of this research. The projects, developed simultaneously with this research, represent different ways of user interaction with different types of 3D digitized CH assets (chapter 3). The data on experience and perception was collected from the stakeholders before during and after interacting with the applications presented in these projects. The data collection at this stage was performed through a series of interviews in museums, logging the user interaction, and a collaborative workshop (chapter 5). The evaluation of such data was used to theorize several criteria for enhancing the cultural experience through 3D digitized CH.

Finally, the guidelines for effective 3D digitization, along with the evaluation criteria for cultural experience were assembled in form of a cohesive theoretical framework (chapter 6).

The term framework has many meanings and it has been defined differently by scholars in different fields. In the field of Human-computer interaction, it is commonly used to describe a form of guidance that is explicated in a particular way to inform design and analysis [Rogers and Muller 2006]. The frameworks are usually applied to enhance the process of designing a better system in terms of efficiency and usage by improving the quality of discussion among professionals and researchers. A framework is typically derived from a theory or a set of assumptions about the structure and/or function of phenomena. Frameworks can be categorized into two main types as described by [Rocco and Plakhotnik 2009]: "a theoretical framework synthesizes existing theories and related concepts, and empirical research, to develop a foundation for new theory development", and "a conceptual framework relates concepts, empirical research, and relevant theories to advance and systematize knowledge about related concepts or issues."

In this research different guidelines and evaluation criteria for an enhanced museum experience were theorized by applying empirical mixed methods research. The proposed framework should be able to suggest various aspects of designing cultural experiences through 3D digital interactions. It should also provide possible design choices for such aspects. Therefore, the resulted framework is intended to be a theoretical one for CH professionals, designers, digital application developers, and researchers to support their decision-making about important criteria for the design, development, and implementation of interactive digital systems with 3D digitized CH.

The framework is an attempt to partially answer the research questions, driven by the theories grounded in various types of data explicated previously. Such theories were clustered into several categories and subcategories to demonstrate what are the important aspects to design experiences through 3D interactive systems with CH assets. In this manner, the lessons learned from the past and considerations of general aspects of experience can be used to develop more conscious/effective design solutions and collaborations without much experimentation.

The framework can be applied to future projects and research for enhancing the specified experiences in the context of this research. In this sense, the framework is also an applicative one. But, in the duration of this research, it is not intended to provide specific tools to make the evaluation criteria and guidelines actionable in a design process. However, the applicability of the framework has been demonstrated by using it to evaluate a couple of past projects (chapter 6).

2. LITERATURE REVIEW ABOUT 3D DIGITIZATION AND MUSEUM EXPERIENCE DESIGN

This research is dealing with two aspects: the 3D digitization of cultural heritage, and the use of 3D technologies for enhanced cultural experiences.[2]

State of the art 3D digitization of CH includes the studies to demonstrate the advancements and unexplored potentials in massive digitization of various forms of CH assets, by evaluating the important projects and research around the world.

The studies in museum experience are summarized based on the strengths and weaknesses of past projects and experiments with the use of 3D technologies for museum goals and user experience. Such studies were explored by considering the methods adapted, types of uses, target groups, types of the 3D applications, and aspects of experience covered in these studies. To exploit the interactive nature of 3D models of CH assets, several technologies such as AR, VR, and 3D printing have been tested in museums for enhanced visitor experiences and CH research. Most of these studies remain focused on the quality and technical aspects of such 3D applications. The studies that highlight the importance of 3D technologies for cultural experience are often concentrated on a specific aspect of experience without making a comparison with other possibilities offered by such technologies. A few studies that analyzed the multiple digital technologies for interactive experiences were also examined. These studies produced different types of models and frameworks, which are also listed here in terms of their scope and applicability.

2.1.1 3D digitization of CH

3D digitization of CH assets has a history dating back to the end of the 20th century. The first attempts at 3D digitizing the museum objects in the laboratory-based systems were proposed by the National Research Council of Canada (NRCC), starting from the end of the 1980s. These attempts included:

- 3D range finder capable of digitizing artifacts at high resolution [Boulanger et al. 1988]
- laser scanning system for examination of paintings through accurate recording of the 3D surface data and the color properties [Baribeau et al. 1992]
- range sensor developed for capturing the 3D shape and color of objects with high resolution and inherent registration between shape and color [Baribeau et al. 1996; Taylor et al. 1996]
- systems for 3D imaging and modeling of museum collections such as paintings and archaeological objects
- technologies for field recording of archaeological sites, architectural elements, large sculptures, and natural history specimens [Godin et al. 2002; Toylor et al. 2003].

[2] This section is a brief background of these two aspects. The specific literature review related to each activity and methods adapted in this thesis is presented alongside the explanation of such activities.

Early applications

After the laboratory-based systems, a project of large statue modeling that became prominent among the professionals as the first real application of 3D digitization in CH was the Stanford Digital Michelangelo Project [Levoy et al. 2000]. Under the scope of this project, 20 sculptures by Michelangelo were digitized, including a 5 meters tall statue of David. The technique used in this project was laser scanning based on the principles of triangulation. The laser scanner was coupled with a mechanical gantry of appropriate size, mobility, and reconfigurability. Such a system was able to capture the details smaller than a millimeter, at a safe distance from the statues, and could reach height for capturing the details at the top of the tallest statue (5m high). The Digital Michelangelo project demonstrated, to both the professionals and the general public, the importance of rich information storage and interactivity provided by a "third dimension" in the digitization of CH assets.

At the beginning of the 21st century, professionals and researchers noticed several problems in using 3D digitization for CH assets. Such problems included:

- the capacity of sensors for scanning large objects
- the sophistication of classic image alignment techniques
- integration of various techniques for enhanced information
- imaging of difficult surfaces (dark/shiny)
- association of the chromatic surface information to the acquired geometrical information
- memory management for processing and storing large data
- complexity of logistics

Two benchmark projects attempted to deal with some of these problems in the early days of the 3D digitization of CH. The first project was the digital acquisition of the wooden statue of "Maddalena" by Donatello [Guidi et al. 2001]. This project specifically evaluated the errors in 3D capturing devices and their propagation over a range of 3D images in digitizing a large sculpture. Evaluation of the agreement between the 3D model and the actual object was performed for the first time in this project by integrating active range sensing and photogrammetry. The second project was the 3D modeling of the bronze statue of "David" by Donatello [Cioci et al. 2005]. The statue digitized in this project is made of bronze, which has a very poor optical response to 3D digitization devices. Laser triangular devices were not efficient for digitizing this sculpture due to its dark and specular surface. The surface properties would have resulted in a reduction in the amount of light returned to the range sensor and an increase in 3D data uncertainty. Therefore, this project employed frequency-modulated laser radars to successfully digitize the sculpture.

The progress made to date

After extensive experimentation with the technology at the early stages, the importance of 3D digitization was evident to the scientific community [Pieraccini et al. 2001]. The professionals and researchers started to explore the potentialities of 3D digitization in various fields of application such as:

- digital archives of 3D models

- high fidelity physical replica of art-works
- remote fruition of cultural heritage
- digital restoration
- monitoring of cultural heritage

As a result of the early development and lessons learned from practical applications, significant progress has been made in the 3D digitization of CH in terms of (i) speed of 3D data acquisition; (ii) time of post-processing; (iii) reduced measurement uncertainty, (iv) quality of colored surface texture capturing.

Such progress was demonstrated in a recent book chapter on the 3D digitization of CH [Guidi and Frischer 2020]. This chapter reported a thorough literature review of the past works in 3D digitization of cultural heritage for (i) physical CH assets such as sculptures [Fontana et al. 2002; Guidi et al. 2009d; Ikeuchi et al. 2007], CH objects [Koller et al. 2006; Zhang et al. 2018], paintings [Guidi et al. 2004a; Blais et al. 2007; Abate et al. 2014; Callieri et al. 2015], built heritage [Guidi et al. 2002; Capra et al. 2005; Dellepiane et al. 2013], and underwater heritage [Drap et al. 2015; Menna et al. 2018]; (ii) intangible heritage such as performing arts, social practices, rituals, festive events and traditional craftsmanship [Shaw 2016; Dhanapalan 2016; Dimitropoulos et al. 2018], and (iii) reconstruction of lost CH assets [El-Hakim et al. 2008b][Guidi et al. 2014][Frischer et al. 2016]. Such literature review demonstrated that 3D digitization is now becoming a common practice in recording, monitoring, and preserving the CH assets, after the initial resistance by the institutions and authorities towards new technologies. With evermore investment in cultural activities and acceptance of the importance of 3D digitization of CH, such a shift of perspectives is more evident in the Eurozone and UK. At the same time, such a “digital turn” presents several challenges such as the need for interdisciplinary approaches to bring together humanities, design, and engineering disciplines, and the long term preservation of the “digital heritage”, which in some cases is more fragile than the physical heritage.

Systematic and massive digitization

At the same time many projects, especially at the European level, have been dedicated to the development of technologies and methodologies aimed at the systematic digitization of the museum contents. The systematic digitization of CH started from the EPOCH network of excellence (2004-2008) [EPOCH WEBSITE TEAM 2004]. It was a network of more than 85 cultural and research institutions from most of the European countries to overcome the gaps in research of technology for CH and define a framework to improve the quality and effectiveness of projects applying digital technology in the field of CH. Several areas were identified to concentrate research efforts to achieve efficient and sustainable applications of digital technologies in CH research and the presentation of cultural information in museums, monuments, and historical sites. In the research agenda of EPOCH [Arnold and Geser 2007], the areas defined to exploit the potential of digital technologies for CH included:

- data collection and recording
- organization, Structuring, analysis, and interrogation
- CH research where digital technologies provide potential intelligent tools
- interpretation and communication

- preservation and archiving
- CH monitoring
- CH on-site and online visitors/users (e.g. requirements of researchers, professionals, the general public, etc.)
- CH exploitation/valorization

Furthermore, the outputs of EPOCH included several digital tools to support the building of cultural heritage applications. These tools were able to produce data (e.g. text, sound, video, 3D), consume data (e.g. for display), or modify existing data (enhancing and/or synthesizing) [Niccolucci and Hermon 2008].

Subsequently, the 3D-COFORM project (2008-2013) was established to bring together the skills and the technical resources for supporting the massive digitization of tangible CH objects by creating technological standards, validation of technologies, defining workflows, and quality control. Another goal of this project was the professional development of cultural institutions through training programs to demonstrate the potentialities of 3D technologies in CH [EU Publications Office 2008]. As a result, the 3D-COFORM developed some of the main tools defined in EPOCH to massively produce reality-based digital models of CH assets.

The project was established to make advancements in the 3D digitization of CH assets by using a series of well-established processing steps of 3D capture/acquisition, processing of the captured 3D data, visualization, and integration of 3D models with metadata and related textual information to describe the different descriptive and technical aspects of the model [Arnold 2013]. By using this standard pipeline, the project aimed at making 3D documentation available as a practical choice for digital documentation campaigns in the CH sector by creating appropriate repositories of 3D models, searchable by databases generated from the relevant metadata records. The digitization pipeline was supported by several tools for 3D data acquisition, 3D modeling, post-processing of 3D models, Infrastructure for creating 3D collections, and presenting 3D models with metadata. Some of the prominent tools developed during the project include:

- Meshlab: a renowned open-source software for 3D mesh visualization and processing, which has been widely used for the production and post-processing of 3D models originating from 3D acquisition [Cignoni et al. 2008]
- In-hand Scanner: developed by KU Leuven, a device to capture 3D data by manually carrying it around the object
- Multiview Dome: designed to acquire the visual appearance (such as color and reflectivity) of optically complicated objects with software tools for rendering through a multi-view approach [Schwartz et al. 2011]
- Ingestion tool: an interactive software to load 3D data and metadata on the EUROPEANA platform [Europeana Foundation 2008], by specifying events and relationships between metadata, digital objects, and derived information [Georgis and Chrysakis 2013]
- CityEngine, a commercial tool for the computer-aided design of 3D city models by using a procedural approach [Esri 2020a]

The 3D-COFORM project demonstrated the real potential and impact of 3D digitization in the CH sector for data collection, recording, support of research, visitor/tourism experiences, and tangible replicas.

After the enormous European efforts, the tools and methods to create and manage 3D digital collections of CH assets proposed by 3D-COFORM were applied to several projects worldwide. 3DICONS project (2012-2015), another European project, was the first attempt at massively digitizing the CH assets by following the practices of 3D-COFORM. The project provided Europeana with more than 3000 accurate 3D models of important archeological objects, buildings, and especially archaeological sites, which include, for example, a significant part of the contents of the Civic Archaeological Museum of Milan [Guidi et al. 2013]. The 3D models produced in this project were associated with the related metadata, which had to be managed in order to make the whole digitized collection usable (in terms of navigability and searchability) for the Europeana portal. The data was managed by developing an effective workflow to collect the metadata for each object in advance, assigning a unique ID to the digitized object, and applying the technical metadata to the descriptive ones at the digitization stage.

Other than European projects, several national projects have made significant progress in automation and efficiency for the massive 3D digitization of CH assets. Cultlab3D, a research project supported by the German ministry and developed by the Fraunhofer Institute for Computer Graphics Research, developed a 3D digitization system to capture objects of various sizes in an automated process [Fraunhofer Institute for Computer Graphics Research 2018]. It was the first attempt to enable fast, automated, and high-quality capturing of geometry, texture, and optical properties of a museum object with an average digitization time of a few minutes per artifact. It was based on a conveyor belt and a series of modular devices positioned along the path to minimize human intervention and to significantly reduce the processing time compared to manual digitization. The digitized objects were also integrated with specific metadata and semantic information for online publishing [Santos et al. 2014].

The 3D Petrie Museum project, started in 2009 by University College London (UCL) and business partner Arius 3D, developed a program of systematic 3D digitization of the Egyptian Petrie collection in London. The objects were digitized using color laser scanning and digital 3D applications were used to create networking of 3D models for audience engagement [UCL 2018]. The project also evaluated the audience's response to the 3D models and applications to understand the potential of 3D in cultural heritage. For this purpose, a virtual research tool (E-Curator) was developed for the arts and humanities community. The stakeholders participated in all stages of the design and development process. Although the project used the best available technologies at the time, it became clear from the user responses that the CH professionals and researchers required high-resolution geometry/texture of 3D models and a combination of different types of image data for detailed examination and comparison [Robson et al. 2012].

Similarly, the Smithsonian Institute (USA) started a massive digitization program of its collections with the Smithsonian 3D project [Smithsonian's Digitization Program Office 2009]. The Smithsonian Institution has the world's largest collection of museum objects and archives (155 million), but less than 1% of its collection is on display at any one time. Therefore, the massive 3D digitization program was valuable to bring the remaining 99% of the collection to the general public and for creating new cultural stories by linking the various objects in the digital world.

Finally, most recently, the Uffizi Gallery in Florence with an agreement with Indiana University(IU-USA), started 3D digitization of its complete Roman and Greek sculptural collection

(IU-Uffizi Project) in which the Reverse Engineering and Computer Vision group of Politecnico di Milano is involved as a technical partner [Virtual World Heritage Lab 2019]. Even though massive digitization of small/medium-sized objects has been attempted in the past, this project is the first of its kind to massively digitize large objects (ca. 1250) in difficult museum conditions [Guidi et al. 2018]. Being part of this research, the IU-Uffizi project is explained in detail in the next chapters.

Though enormous progress has been made in the sophistication of 3D digitization and its applications in CH, it is clear that still an extensive amount of time and resources are required for 3D data capturing and post-processing to obtain high quality of 3D models. This is specifically true when the objective is to digitize multiple objects or the whole collections of museums.

Furthermore, the analyses of past and current experiences in the massive digitization of CH made it clear that automatic photogrammetry has several advantages over active 3D scanning. In particular, the experience with recent EU-financed projects such as 3DICONS, the CultLab3D project, and the IU-Uffizi Project, with the goals of digitizing the entire collections of museum objects, confirmed the advantages of automatic photogrammetry based on Structure from Motion (SfM) / Image matching (IM) [Jebara et al. 1999; Pollefeys et al. 2000; Cohen et al. 2012; Lowe 2004] for massive digitization of CH. Automatic photogrammetry can produce the 3D textured models of high quality 5 to 20 times faster than the time required by slow active 3D devices [Guidi and Frischer 2020].

2.1.2 Interactive museum experience design

The 3D models produced as a result of the digitization process present only the starting point of other possible applications in museum experience design and CH research. These applications include virtual and augmented experiences for museum presentation, education, visitor engagement, and physical reproductions of CH assets. Therefore, in the past few years, the research in 3D digitization has focused on optimization and simplification of the process to create high-quality 3D models of real-world objects in a short time. At the same time, researchers have focused on the new aspects of museum experience and advanced solutions for the visualization of 3D data through various technologies.

Museum informatics (museums, people, and technologies)

Around the same time that 3D digitization was being tested on museum objects (at the end of the 20th century), there was also a growing debate about the primary functions of museums. The researchers started considering museums as the places which do not only serve the purpose of preserving the tangible heritage and as repositories of objects but also as the institution to transmit knowledge to the members of society to survive and progress [Cannon-Brookes 1992; Greenhill 1992]. With the quick changes on cultural and technological fronts at that time, museums were compelled to respond to the information needs of the society to stay relevant. The function of the museums to keep pace with the technology and evolving cultural needs of the society was described as "information utility" [MacDonald and Alsford 1991].

As a result, the museum collections, which were previously perceived mainly as physical objects, started to also have an "information dimension". With the digital revolution, this new information dimension was created in new ways that were not possible before. The museums started to experiment with virtual products and services for enhancing the experience of their visitors and to transfer knowledge through digital means in a new changing society. The concept of virtual and web museums also started to emerge in the same period [Schweibenz 1998]. Digitization became a powerful tool for the conservation of museum collections, research through electronic databases/networks, and publication on the internet. The museum professionals also began to learn new skills to manage digital information resources in museums [Keene 1996].

Along with the changing information and educational roles of museums, visitor studies also started to gain importance. The visitors' interests, needs, preferences, and expectations were studied intensively by several researchers. By performing extensive visitor surveys, visitor motivation was also studied to determine reasons for people visiting the museums and the importance of different kinds of experiences for the visitors during their visit. For instance, Melora McDermott conducted several surveys to assess visitor motivation and information needs to provide useful insights into museum practices to plan for the development of new exhibitions and programs [McDermott 1988; McDermott 1990]. The results of these surveys show that visitors found the information communication to be an important part of their museum experience. Without the information, the visitors can not relate to the museum objects due to the lack of meaning-making and understanding. Hence, it was apparent that museum objects had to be presented in context for "visitor meaning-making" [Silverman 1995], instead of only presenting the objects and letting "objects speak for themselves" [Chapman 1981]. Museums started to present their assets in context and research focus shifted towards museum communications to create a better understanding of museum objects among the visitors. Such connection between visitors, objects, and information was named "connectedness" by [Hoptman 1992].

At the beginning of the 21st century, it was clear that the museums had a new role of transmitting information through digital media to present museum objects in context and in accordance with their visitors' expectations and information needs. As a result, a new discipline of study called "museum informatics" was introduced, which is defined as "the study of the sociotechnical interactions that take place at the intersection of people, information, and technology in museums" [Marty et al. 2003; Marty and Jones 2008].

Following the introduction of museum informatics, the museums started to transform into a digital age, and visitor-focused studies gained importance. Several trends started to emerge in the museums during the first decade of the 21st century:

- research focusing on technological development for museums and acceptance by the museums and visitors to the use of emerging technologies [Arthur et al. 2004; Pianesi et al. 2009]
- radical transparency of information i.e. the shift from museums providing little or no access to information to much more open access [Lynch 2013; Marstine 2013]
- equal importance by the museums to digital information as to their tangible assets. Museum information management moved from process management to strategic management oriented towards meeting the needs of external audiences [Bradburne 2001; Reussner 2003]
- studies to evaluate the visitor experience based on the motivations of audiences to visit physical or virtual museums [Ellenbogen et al. 2008]
- a shift in the focus of CH professionals towards dissemination of information as compared to only preservation of objects [Coburn and Baca 2004; Knell 2013]
- collaborations between the museums to share data about their collections to comply with the information needs of audiences [Allen 2000; Rodger et al. 2005]

- information interaction in the museums to enhance the visitor experience and engagement [Falk and Dierking 2000]

Museum Interactives

The most significant change that happened in the context of museum informatics was the introduction of a new relationship between the visitors and museum objects through interactive digital technologies. Such interactives removed the traditional barriers of time and space by allowing visitors to digitally interact with the artifacts from different collections, regardless of their physical location. The digital technologies also allowed people for the first time to interact with museum objects outside the museum walls, similar to what was visioned by the French philosopher André Malraux [Malraux 1967]. Virtual museums and digital interaction in the museums extended the museum audiences by creating new types of visitors without replacing the physical exhibitions. In the early times of introducing interactive multimedia applications in museums, Economou [Economou 1998] studied the impact of digital interactions on museum visits. The research showed that the digital interactions in museums attracted and engaged more visitors compared to only physical exhibitions. Furthermore, the visitors spend considerable time learning about the objects with digital interaction, which in most cases is an added time without taking away the time from physical exhibitions.

With the early introduction of museum interactives and virtual museums, the researchers also started pointing out several issues related to the appropriate use of such interactions. [Economou 1998] evaluated a multimedia interactive application by testing it with a variety of users. The study showed the positive effects of interactive media on the visitor experience and its power of attraction to attract new audiences. Yet, the effectiveness of museum interaction depends on the type of information that museums want to communicate by considering the technical, aesthetic, financial, and educational implications. She concluded that the digital interactions must be considered only as a tool for the presentation and interpretation of the museum objects and museum professionals must be aware of the positive and negative aspects of digital interactions to find a balance between “uncritical enthusiasm” and “technophobic resistance”.

The issues in implementing the digital museum interactions that were pointed out at the early stages include:

- studies in digital interactive media for museums showed that the visitors spent more time on personalized interactive technologies, but at the same time researchers also investigated if the increased time was a result of the actual learning and interpreting or an additional time to figure out the use of the digital devices [Evans and Sterry 1999].
- social implications (enhance or undermine the social experience in a group visit) of using the digital applications in the museums [Woodruff et al. 2002; Vom Lehn et al. 2005]
- careful examination of digital interface design with dynamic adaption for various user needs (personalization - for both museum professionals and visitors) [Paternò and Mancini 2000]
- privacy concerns and ethical implications of using personal information (background, interests, desires, needs, etc.) of the visitors through user profiling to deliver personalized information [Toch et al. 2012; Kuflik et al. 2010]

While such issues were being discussed among the researchers, there was a growing interest among the museums to create new forms of participation through digital museum interactions. Several digital tools and technologies were being tested to enable designers and museum professionals to create new forms of visitors' engagement, museum learning, and enhanced experiences. The interactive technologies provided innovative and flexible ways to provide comprehensive information about the museum objects and collections both inside and outside the museums. Such technologies were also integrated into the museum exhibitions for enhancing the visitor experience and curiosity to learn about the museum objects [Ciolfi and Bannon 2002].

Digital tools and technologies for the enhanced museum experience

The most popular and early application of interactive technology introduced in the museums were the information kiosks. Museums started to introduce interactive information kiosks as a part of the museum experience, especially to attract young visitors who mostly do not perceive museums as places to spend their leisure time. Kiosks are used as the secondary source of information in museums and they can be implemented as a computer touch screen near the object of interest or in the information section of a museum exhibition. Many types of information kiosks were tested in the museums [Shigesada et al. 2003; Katre and Sarnaik 2009] and the concerns about their usability and accessibility were analyzed [Burmistrov 2015].

The introduction of the worldwide web in the 1990s and its subsequent use by the museums significantly enhanced the access to the museum information beyond the museum walls. It offered an opportunity for the museums to display their collections and create applications that could be viewed by people around the world. Starting from the 21st century, museums started using the internet as an effective means of communication with the people, to create virtual exhibitions, and to make their presence known [Fotakis and Economides 2008]. As the website presence of the museums was rapidly increasing, the researchers also evaluated the user experience with virtual museum websites in terms of the engagement, education, psychological effects, technological affordances, accessibility, usability, and maintainability [Lin et al. 2012][Sundar et al. 2015][Sylaiou et al. 2017][Kabassi 2017]. These studies provided useful insights for designing the museum website to achieve the museum's goals of education and audience engagement. For enhancing the online visitor experience, researchers also studied people's motivation to visit museum websites [Fantoni et al. 2012].

The widespread availability of the internet and its platform-independent nature provided a possibility to use it also to develop applications inside the museums. Other than the introduction of purely virtual systems accessible through the internet, the researchers also explored the use of digital technologies paired with the internet for museum exhibitions. With the availability of the worldwide web and the societal trend of customization/personalization of products and interactions, the use of mobile computing and handheld devices in the museums was widely explored [Proctor and Tellis 2003; Tellis 2004]. At the beginning of museum interactives, the most experimented with devices for different purposes (museum guides, education, collaborations, visitor engagement, and personalized experiences) were the Personal Digital Assistants (PDA) [Ciavarella and Paterno 2003; Yatani et al. 2004; Papadimitriou et al. 2006; Tesoriero et al. 2007]. PDAs were widely adopted in museums around the world due to their small size but larger screen with more colors than a mobile phone. Meanwhile, the mobile and handheld devices were also tested by the researchers for design and usability evaluation. The devices were evaluated from different perspectives such as the applicability, educational value, audience engagement, visitor growth, and overall impact on museums [Stoica et al. 2005; Cabrera et al. 2005].

The mobile and handheld devices could be personalized for individual museum visitors based on their profile, knowledge, interests, needs, and other personal characteristics. Personalization and adaptation techniques were used more and more through mobile devices in museums [Martin and Trummer 2005]. Several methods and techniques of personalization and adaptive hypermedia were introduced as part of the museum experience. Ardissono et al. [Ardissono et al. 2012] carried out an extensive literature review to summarize the evolution of personalization in CH to highlight the challenges of implementing it and point out the areas where further research is needed. Some examples of personalization by using mobile devices include indoor interaction through physical movement by determining the accurate position of the visitor [Petrelli and Not 2005], outdoor personalization [Cheverst et al. 2000], providing context-aware CH information both indoors and outdoors [Ruotsalo et al. 2009], context-sensitive dynamic user model for personalization [Oppermann and Specht 2000], dynamic content creation based on user's focus of attention [Stock et al. 2007], personalization through tangible and embodied interaction [Hatala and Wakkary 2005], and personalization with social experience for indoor visits [Kuflik et al. 2011].

The challenges in implementing personalization for the needs of the CH industry include:

- development of standards for content representation, system architectures, and personalization techniques
- Use of personalization as a tool to deliver and manage a long-lasting experience (lifelong experience), before, during, and after the visit [Kuflik et al. 2010; Wilkening and Chung 2009; King and Lord 2015]
- Problems in the evaluation of adaptive systems: lack of objectivity, lack of distinction between usability and adaptivity issues, and incorrect sampling of participants [Weibelzahl 2005; Weibelzahl et al. 2020]
- enabling collaborations in both physical cultural heritage sites and online virtual experiences [Fisher and Twiss-Garrity 2007]
- supporting realistic scenarios and evaluating the needs of real visitors and users both as individuals and groups in daily interactions with CH
- experimenting with new ideas and new technology beyond hypermedia and multimedia

Cultural experience with 3D technologies

In the CH sector, new technologies have also been implemented in ways that go beyond the two dimensions of PDAs or information kiosks. The development of interactive 3D technologies has changed the traditional ways of researching and perceiving CH assets. The new 3D technologies assisted the professionals in performing their activities in creative ways and attracting the broader public. The most experimented 3D technologies in the CH field include Virtual reality (VR), Augmented reality (AR), and 3D printing.

AR is "a live view of a physical real-world environment that has been enhanced by adding context-sensitive virtual computer-generated information to it" [Carmigniani and Furht 2011]. AR allows the user to see the real world, with virtual objects superimposed upon the real world, therefore, AR supplements reality, rather than completely replacing it [Azuma 1997]. It is an interactive technology registered in 3D that combines the real world with virtual objects. The users of augmented reality can interact with the augmented information of their surroundings in real-time. In contrast with VR, digital information is superimposed upon physical reality. Both of these technologies in general aim at enhancing the user's perception of the real world by adding virtual information and interactions.

AR has been applied to many fields over the years for education, entertainment, and marketing. The implementation of AR in the CH sector probably started with the ARCHEOGUIDE project [Vlahakis et al. 2001]. For the first time, this project provided the visitors an augmented visit to ancient ruins with reconstructions based on their position and orientation in the cultural site. Apart from the visitor experience, the project also aimed at enhancing the understanding of researchers and CH professionals to better understand different aspects of the past through digital reconstructions at the site. Starting from this project many efforts have been made to implement AR for three major application areas as reported by [Bekele et al. 2018]:

- enhanced visitors' experience at a museum or a CH site (both indoors and outdoors), typically through virtual elements (description, map, personalized content, or virtual character) superimposed over the real world view of the user [Kim et al. 2009; Angelopoulou et al. 2011; Damala et al. 2012; Caggianese et al. 2014; Breuss-Schneeweis 2016; Pierdicca et al. 2015b; Damala et al. 2016]
- enabling users to visualize and interact with the reconstructions of lost/ruined historical objects and monuments and their intangible characteristics [Portalés et al. 2009; Haugstvedt and Krogstie 2012; Han et al. 2013; Kang 2013; Madsen and Madsen 2015; Canciani et al. 2016]
- providing the user with a possibility to visualize and explore the current and past state of CH assets to analyze, discover, interpret and gain new knowledge [3] [Choudary et al. 2009; Ridel et al. 2014; Pierdicca et al. 2015a]

On the other hand, "VR is a human-computer interface that virtually simulates realistic environments where the participants can immerse and move around" [Zheng et al. 1998]. The representation of realistic environments in virtual reality can be seen from different angles and can be reached grabbed and reshaped by the user. It can enhance the educational, entertaining, and aesthetic experience and can improve the perception of reality by bringing the user into a simulated world that can be manipulated digitally.

During the past two decades, many experiments have also been made with VR to explore its potential both in leisure and professional context. In the CH sector, VR has been used:

- to plan and manage museum exhibitions, cultural events, and tours such as testing the potential popularity of special exhibits or testing the preferences of target groups towards certain CH sites [Sussmann and Vanhegan 2000]
- to motivate visitors/tourists to visit museums or cultural destinations by providing an experience of the destination in advance via virtual museum [Guidi et al. 2010; Gonizzi Barsanti et al. 2015; Katsouri et al. 2015; Kim and Hall 2019]
- for providing users with an educational material to learn about the historical aspects of tangible and intangible CH [Richards-Rissetto et al. 2014; Baldissini and Gaiani 2014; Bustillo et al. 2015]

[3] Exploration is different than reconstruction i.e. it solely target experts not the general public and the visualization and interaction is only intended for discovery of new insights.

- to potentially preserve the endangered CH sites by decreasing the overall visitation to those sites, given that the tourists may accept the immersive experience as a substitute for real visitation [Guttentag 2010]
- to observe CH assets and interpret them better by receiving additional information in immersive environments for exploration purposes [Marton et al. 2014; Guerra et al. 2015]
- for enhancing visitors' experience in museums and CH sites by providing unique scenarios [Jung et al. 2016; Lee et al. 2020]

In a recent publication [Lee et al. 2020], investigated the consequences of absorptive experiences (seizing users' attention by bringing the experience into the mind for education and entertainment) on immersion (being a part of the experience virtually) in VR. They showed that the education, entertainment, and esthetic experiences have a great influence on the immersive VR experience of museum visitors and on their intention to physically visit the museum.

Both AR and VR are used in similar situations allowing the users to move in physical space while viewing additional digital information on CH objects of interest or making a virtual tour of the museum with wearable technology from the comfort of home [Guerra et al. 2015]. Regardless of the domain of use, as defined by [Bekele et al. 2018], the essential aspects of AR, VR, and mixed-reality applications are tracking and registration, virtual environment modeling, computers, display, and devices for input and tracking, and interactive interfaces.

The recent advancements in digital fabrication technology and reduction of 3D printing cost has created many opportunities for rapidly producing commonly used objects for the wider public. 3D printing has been widely used for industrial prototyping to create a tangible representation of a concept because it does not require a setting up time and cost as in traditional manufacturing. The 3D printing process is also independent of the geometric complexity of an object. Therefore, for creating a single or a few prototypes, 3D printing has become an effective tool in many industrial fields. 3D printing has also been used in the customer market for publicity of products. Apart from commercial or industrial uses, people have also been using 3D printing to produce objects of daily use in small numbers at home.

In recent years, because of the reduction of material and equipment costs, apart from rapid prototyping, 3D printing has been used in many other contexts including CH. Allard et al. [Allard et al. 2005] carried out one of the earliest experiments with the use of 3D printing for museum exhibitions. They used a non-invasive hand-held laser scanner and 3D printing to create the replica of a skeleton for displaying the culturally sensitive human remains. The ultimate objective of this experiment was to enhance the visitor experience with low-cost reproduction without displaying sensitive content. Since then, 3D printing has been intensively used for creating reproductions of CH assets for documentation, restoration, preservation, education, and dissemination [Neumüller et al. 2014; Scopigno et al. 2017; Fatta et al. 2018; Balletti et al. 2018]. The potential of 3D printing in the field of CH has been explored for:

- reconstruction of damaged or lost CH assets and preservation by producing high-quality reproductions of art pieces [Yang 2015; Al-Baghdadi 2017; Xu et al. 2017; Denker 2017; Clini et al. 2018; Elkhuizen et al. 2019; Liu et al. 2020]
- diffusing and discovering knowledge for accessible documentation and research of CH assets [Hess and Robson 2013; Adami et al. 2015; Rossi and Barcarolo 2019]

- providing haptic access to CH assets that can not be touched because of several reasons such as conservation of sensitive objects, too big or too small size of objects [Cantoni et al. 2018; Balletti et al. 2018; Wilson et al. 2018; Wilson et al. 2020]
- developing tactile experiences for museum education to enhance understanding and participation in learning contexts that can benefit from tactility [Reichinger et al. 2011; Turner et al. 2017; Knochel et al. 2018; Poce et al. 2021]
- communications to motivate museum visits and other public outreach activities [Stanco et al. 2017; Tanasi et al. 2018]

Ever since the introduction of digital tools and technologies for museum interactives, the sophistication of technologies is continuously evolving the museum experience. "Media-rich exhibitions represent a strategy for creating museum-comfort today for tomorrow's museum-going public" [Falk and Dierking 2016]. But, any type of technology can not survive in isolation. As interactive technologies are tools of mediation between museum and visitor, researchers CH professionals, and designers must consider the consequences of implementing digital technologies in museums and must analyze users' personal, social and cultural contexts before designing any interactive experience [Falk and Dierking 2016]. The understanding of visitors' needs, how they use the interactives, and how interactives can be integrated into museum exhibitions is of utmost importance for a successful implementation of interactive technology. To achieve these goals, CH professionals must be aware of the ever-changing needs, interests and behavior of their visitors. Museum interactives must not be implemented just because they represent an advanced and exciting technology. If the end-users have no interest in a specific technology then it makes no sense to spend a tremendous amount of money on that technology that will never be used.

3D technologies provided the users with new possibilities such as: having a feeling of being in a recreated space through immersive environments, learning about the museum objects with a greater degree of interaction by augmenting the real world, and tangible interaction with the physical replicas or reconstruction of CH assets. Such interactions can help the professionals to perform research in new ways and can have a strong sensory and emotional impact on visitors, which can enhance the museum learning process [Maschner et al. 2013; Mortara and Catalano 2018].

But, the effective learning outcome from the 3D interactions depends on designing the 3D applications through interdisciplinary collaborations between disciplines such as history, art, and languages, and must include both tangible and intangible content like myths, beliefs, and social values. The evolution of technology and blurred boundaries between different disciplines has produced the need for new modes of interaction and better communication methods. The affordance of virtual 3D applications, motivations of users, and type of immersion are also important factors for making virtual 3D environments a direct and engaging setting for informal learning in CH [Mortara and Catalano 2018]. On the other hand, 3D technologies for generating physical replicas must be precise to produce replicas of CH assets related to the same characteristics of a digital model obtained through the survey analysis [Balletti and Ballarin 2019].

3. DEVELOPMENT OF PROJECTS: 3D DIGITIZATION OF CULTURAL HERITAGE AND USER INTERACTION

Before starting the evaluation of efficiency and discussion about the effectiveness of 3D digitization for an enhanced cultural experience, different modes of interactions with various forms (sculptures, paintings, monuments, and other museum objects) of 3D digitized cultural heritage are presented in this chapter. This chapter is a brief explanation of national, international, and pilot projects in which the author collaborated during the course of this research. The objectives of these projects are in line with the four significant uses of CH digitization defined in chapter 1 (museum education, CH research, conservation/restoration, and museum presentation). The projects were not only used for developing the guidelines of best practices in the 3D digitization of CH assets, but also for the collection of both qualitative (interviews, questionnaires, workshop) and quantitative (questionnaires and application log) data from the stakeholders of this research. The data collection protocols and evaluation processes are presented in the next chapters.

3.1 IU-Uffizi project

IU-Uffizi project is a large-scale 3D digitization project involving ca. 1250 ancient sculptures, sarcophagi, altars, inscriptions, and fragments. These objects are located in different places, including the Uffizi Gallery, the Pitti Palace, the Boboli Gardens in Florence, and a storage facility inside Villa Corsini in Castello, a small village close to Florence. The project is coordinated and sponsored by Indiana University with the technical support of Politecnico di Milano and the advice of a scientific committee of experts in the fields of art history and archaeology. In the framework of this project, high-resolution and textured 3D models of the target pieces are being produced along with the corresponding descriptive and technical metadata. The goal of the project is to produce a large 3D database of these sculptures for scientific, touristic, and conservation purposes.

To implement a project for a museum as multifaceted as the Uffizi Gallery it is important to respect the museum's present-day image, its intentions for the future, and at the same time the history and display of its collections. Achieving this balance makes it possible to plan effective and user-friendly communication methods, which are required to promote the museum's heritage in a way that appeals to a broad spectrum of the general public.

Today digital applications are used for this purpose in several fields such as education, promotion, advertising, and research [Donati 2006]. The Indiana University-Uffizi project was developed by the museum in an effort to highlight an important collection of ancient Greek and Roman sculpture, which is often not given the attention it merits by visitors to the gallery, who understandably, are most interested in seeing the masterpieces of painters such as Giotto, Leonardo, Botticelli, to name a few. The project thus confronts two challenges: amplifying the visibility and comprehensibility of the sculptural holdings for museum visitors; and using digital publication on the Internet to make the sculptures better known to students, scholars, and the general public wherever they may live. Translating the challenges into operational terms means asking:

- what digital solutions should we use, and how?
- are we certain that 3D modeling is the most appropriate solution?
- are we sure we want to run the risk of using a medium that can become the attraction and no longer simply the vehicle?

This needs to be considered and, if possible, avoided. The digital era has led us to witness a *revolution of relevancy*, based on understanding its effect and the boundaries of its use [CENSIS 2015].

The new 3D technologies have facilitated a new type of connection between viewers and archaeology: their use can, ideally, lead to an enhanced visitor experience by stimulating participation and mutual exchange. The role of the visitor is converted "*from passive recipient of a cultural project to active protagonist of a museum's course of evolution [...] moreover modifying the nature of the relationship established between the museum and its visitors"* [Solima 2008].

The strengthened participation and first-person experience enrich the understanding and interpretation of cultural heritage, transforming the user into the editor of the subject matter [Affleck and Kvan 2008]. All this is enhanced by the visitor's awareness of participation in the experience: the vastly popular custom of sharing highlights of one's daily life through social media makes it possible, even during a museum visit, to be part of a personal "*digital journal*". Hence, the visitor establishes an almost personal relationship with the museum by becoming a protagonist who shapes his own experience and, in a sense, reinvents the museum itself. This is the basic concept upon which the Indiana University-Uffizi Project was developed: to respect the museum's needs, the contemporary visitor's desire for engagement, and to increase knowledge and spread cultural awareness beyond the confines of the museum itself by utilizing the Internet. The international news coverage of the project and the results of activities carried out during this project showed that people were more eager to visit the archaeological collection and started to pay more attention to its masterpieces such as Medici Venus or Medici Apollino (Figure 3.1) [Povoledo 2016; Russo 2018; Neuendorf 2018].

During several public lectures and meetings held at the museum, visitors also had the chance to talk directly to the scientists engaged in the project, in which various aspects of the project were discussed. The project has also prepared a website on which all the sculptures modeled can be viewed and several tests have been made with the use of AR and 3D printing of important objects for different types of experiences [Virtual World Heritage Lab 2019]. Meanwhile, the Uffizi museum has also embedded several 3D models created under the scope of this project onto its own publicly available website [Le Galleria degli Uffizi 2021].

(a) (b)

Figure 3.1: Examples of important sculptures that attracted public attraction as a result of the IU-Uffizi project: (a) Medici Venus; (b) Medici Apollino[4]

3.1.1 Principal technique

Apart from some instances when laser scanning was used (scaling of models for example), the main 3D capturing technique used in the IU-Uffizi project is Structure from Motion SfM/IM photogrammetry, which allows acquiring both the geometrical and surface texture of the captured objects. Even though the photogrammetric process is highly automatic, the results can still be affected by the photographic quality of the images, the proper distribution of camera locations in space around the artifact being surveyed, and the skills of the post-processing operator.

The 3D acquisition pipeline based on active devices [Bernardini and Rushmeier 2002a], requires a considerable amount of manual work in some of these steps, with particular emphasis on

[4] Photo Source: Uffizi gallery website - https://www.uffizi.it/en

alignment, mesh, and texture editing. Contrarily, the SFM-based approach is fully automatic after acquiring the images in the correct sequence. The output of this process is a textured 3D mesh for which a moderate amount of editing might still be needed, but the extent of the editing work is smaller than that for scanned models. Even though high resolution can be achieved by using triangulation-based laser scanning, the texture still has to be re-created from images on a 3D scanned model. This process requires to orient all of the texturing pictures by the 3D model orientation and projecting them on the portions of mesh that are visible at the corresponding point of view of the images. Finally, the overlapped images are blended in terms of exposure and color temperature. As a result, generating a texturized model from a mesh obtained from an active device is much more time-consuming than the automatically generated texturized model from SFM [Fassi et al. 2013a]. Furthermore, compared to scanning, much less equipment is required for photogrammetry, which can easily be carried to reach the sculptures irrespective of their size and placement. Triangulation-based 3D scanning devices are not suitable for capturing the whole sculpture geometry because of their different sizes and cannot be moved because the museum is open for public display.

3.1.2 Photographic Devices

A careful selection of the camera and mounted lenses is fundamental for achieving optical image quality for photogrammetry. The camera used for most of the photogrammetric survey in this project was a mirrorless Sony α6000 with a 24.3 megapixel APS-C CMOS sensor and E-mount lenses. Depending on the camera object distance (the placement of sculptures in the museum) and the surface quality of the surveyed objects, two different lenses were used: a Zeiss Sonnar 24mm f/1.8 and a Zeiss Touit 12mm f/2.8 Lens. Thanks to the combination of one of the widest fields of view in APS-C format, the latter lens was especially useful for digitizing sculptures near the wall which will be explained further in the next chapter.

All of the images for the outdoor sculptures were captured with natural light. The same approach was adopted for the sculptures placed inside the gallery or museum rooms, wherever possible, the use of artificial lighting was avoided. In situations, especially inside the rooms with no windows, where enough natural light was not present, standard photographic illuminators with controlled color temperature were used. In addition, for acquiring the back sides of the sculptures close to the walls, an HVL-RL1 LED ring light was used. It is a device designed for video recording, therefore it is a continuous illuminator and not a flash. This particular feature is useful for guaranteeing the proper functionality of the autofocus function.

3.1.3 3D capturing procedures

The illumination in the rooms and galleries of the museum was a mixture of artificial spotlights and the natural lights from the windows. Other sculptures placed outside in "Loggia dei Lanzi" and "Boboli Garden" were illuminated by the uniform natural lighting. Based on different lighting conditions, four different approaches were used to adjust the white balance: (i) an Automatic White Balance (AWB) mode was used when the sculpture was illuminated by a uniform mixture of natural and artificial light (in the rooms with a lot of windows) or uniformly illuminated by the natural light (sculptures placed outdoors); (ii) a White Balance set for artificial lighting was used for the sculptures that were predominantly illuminated by the artificial lighting; (iii) for the sculptures illuminated mainly by the exterior light coming from the windows, the White Balance was set for the exterior light temperature and (iv) for the sculptures that cannot be moved and are placed in a position where the light temperature is extremely different on the backside than the front side, a color-checking panel was placed in the scene to adjust the color temperature on raw images before processing.

As no zoom lenses were used in this project, the focal length remained the same for all sets of images in order to avoid a calibration parameter for focal length. The operating mode was set to be “Automatic” with Aperture priority because distortions are very much influenced by the aperture size. The f-value was chosen based on the desired depth of field. In any situation even with very low lighting conditions, the f-value was not set to be more than 5.6.

The sensitivity level (ISO) was set to be as low as possible based on the lighting conditions in order to avoid noise grains on the images, which in turn can reduce the accuracy of 3D measurement. However, for less illuminated objects, the ISO value was set to be higher than the minimum to avoid any movement blurring due to the long exposure time while capturing images without a tripod. For all of the shootings in this project, the “ISO” value was not set to be higher than 1000 for any lighting condition, instead, a tripod was used wherever necessary to avoid increasing the “ISO” value. For outdoor shooting in normal daylight where generally enough light is available, a minimum ISO value was used to obtain minimal grains in the photos.

The software used for aligning images can process only the “jpeg” format of images (which allows a maximum dynamic range of 8 bits per channel), therefore to achieve a higher dynamic range, the “raw” format of images was selected for shooting which allowed to work on the color or exposure corrections in post-processing phase without losing useful information.

3.1.4 Data processing and post-processing

“Agisoft Photoscan”, which is a semiautomatic software package, was used for orienting the images to create dense clouds and meshes. The camera orientation and the internal calibration are made automatically in this software, allowing a little interaction with the user. The software implements image orientation and mesh generation through SFM and dense multi-view stereo-matching algorithms. There are several kinds of objects of different shapes, measures, and materials in the museum, therefore several potentially critical situations may occur. Since the project aims to produce a high number of models in a short time, one of the main factors was to identify the best pipeline with a reasonable tradeoff between processing time and accuracy. Several tests on different types of objects were performed for deciding on a reasonable set of the meshing parameters.

For post-processing, i.e. mesh/texture editing, model orientation, possible fine-scaling, and model analysis, different open source and commercial software packages were used. These include (i) Autodesk Meshmixer;[5] Pixologic ZBrush;[6] InnovMetric Polyworks[7] for Mesh editing; (ii) Pixologic ZBrush and Adobe Photoshop 3D[8] for texture editing and (iii) MeshLab9 and CloudCompare[10] for the final model analysis and orientation. In Figure 3.2 some examples of the final results are shown. The project is still in progress with more than 300 3D models already produced, with an

[5] https://www.meshmixer.com/
[6] https://pixologic.com/
[7] https://www.innovmetric.com/
[8] https://www.adobe.com/
[9] https://www.meshlab.net/
[10] https://www.danielgm.net/cc/

average rate higher than 20 new 3D models per month, which is compliant with the massive 3D digitization operation needed in the framework of this project.

(a) (b)

(c) (d)

Figure 3.2. Some examples of final models with high-resolution texture on Sketchfab (16 megapixels); (a) Laocoön and his sons In the Uffizi gallery; (b) Horse Buontalenti in the basement of Uffizi gallery; (c) Ancient Medici lion in Loggia dei Lanzi; (d) Statue of Juno in Boboli gardens.

Several 3D models generated as a result of the IU-Uffizi project were presented employing various methods to create different modes of interaction between users and digitized CH objects:

- virtual interaction with real objects through augmented reality
- annotated 3D models through touch screen and website
- physical interaction with 3D replicas: 3D printing of digitized models

3.2 Cultural Heritage Through Time - CHT2 project

This section describes the recent works related to the reconstruction of a monument – a Roman circus in Milan. An updated and georeferenced survey of structures attributable to the circus and still visible was carried out under the scope of the CHT2 project[11]. Starting from the acquired data, a three-dimensional model of the monument was defined, referring to other coeval buildings for details not currently available for the circus of Milan. The results of the work constitute, from an archaeological point of view, a first but fundamental step towards a more detailed knowledge of the circus of Milan and offer an indispensable work tool for future research on the monument.

[11] http://cht2-project.eu/

3.2.1 The Roman circus of Milan and the urban area transformation

The Roman circus, a place destined to horse racing competitions and other shows, owes its name to the race that used to take place along a ring composed of two straights connected by two 180-degree bends. There was a separation structure called "*spina*"(backbone) in the center of the track, with a column called *meta* (goal) at the end. One of the short sides of the circus was bordered by the *"Carceres"* i.e., the stalls from where the chariots started the race, while the other, in the shape of a hemicycle, generally included a monumental gateway to the center. On the long sides of this monument, the seats for the public (*Cavea*) were located, and in an eminent position along with one of the two straight sides, there was the grandstand - *pulvinar* [Humphrey 1986].

The circus in Milan, built and probably designed together with the Imperial Palace, was erected in correspondence to the western side of the city following the displacement of the court of the Emperor Maximianus, when Milan became the capital of the empire, between the end of the 3rd and the beginning of the 4th century A.D (Figure 3.3) [Roberto 2018; Sacchi and Rossignani 2012].

The construction of the complex involved a radical transformation of the district: several noble Domus left the place in the surroundings of the palace, while the limit of the walls was moved to the west to leave space for the monumental building [Caporusso 2017; Ceresa Mori 2018]. Besides hosting races and games, the circus was the place to celebrate the power and glory of the Emperor until the Lombard era. For example, the circus hosted the coronation of King Adaloaldo [Diaconus 2021].

The circus of Milan had significant dimensions, it measured about 470x80 meters, despite this, like other Roman monuments, over the centuries it was gradually demolished to the foundations.

Figure 3.3. Roman Circus of Milan: a representation by Francesco Corni.

The entire area originally occupied by the circus has undergone profound manipulation over the centuries. For example, during the Early Middle Ages (VIII-IX century), the Benedictine monastery 'Maggiore' was built. It included a large segment of the city walls with a polygonal tower of the late 3rd century and a quadrangular tower. The quadrangular tower, once belonging to the carceres of the circus, became the bell tower of the church. More restructuring was performed in the Renaissance period such as the expansion of the Monastery which was the largest and oldest monastery in Milan, with the construction of the current church of San Maurizio, decorated with the impressive cycle of frescoes by Bernardino Luini. The monastery was suppressed in 1789, after which the area was used in many other ways such as barracks, a school, a police department, and a military hospital. The monastic complex, corresponding to the northern area of the circus, underwent many radical changes over time. One of the most significant changes was the opening of two new streets (Luini and Ansperto) between 1865 and 1872. The whole circus area was furthermore seriously damaged by the bombings of 1943 during the second world war. Further demolitions and urbanistic renewal of the area occurred during the postwar reconstruction.

As a result of all these changes over time, there are only three sites in the current city where the circus structures are still standing. A part of the remains is preserved in via Circo 9-11 for a height of about 12 m at the point where the hemicycle of the circus also played a defensive role. A little further north in via Vigna 1, a section of the eastern perimeter wall is preserved for about a length of 30 meters and a height of 4m, where six arches of the podium support vaults are clearly visible. The most remarkable testimony, however, is the western tower of the carceres inside the aforementioned complex of the Maggiore Monastery, today part of the Civic Archaeological Museum erected between 1959 and 1964 [Fedeli 2015; Frova 1990; Roberti 1984] (Figure 3.4).

(a) (b) (c)

Figure 3.4. Historical plans of the circus area: (a) 1837/1860 Giuseppe Pozzi (courtesy of the Civica Raccolta delle Stampe A. Bertarelli); (b) 1877, Lithograph C. Fenghi (courtesy of the Civica Raccolta delle Stampe A. Bertarelli); (c) Aerial view of the Archaeological Museum area. The streets that opened at the end of the 19th century are highlighted in red dash line: from north to south via B. Luini and east to west via Ansperto.

Despite the few visible remains, the memory of the circus has been guarded by numerous historical sources and preserved by some characteristic toponyms (via Circo, the medieval churches of Santa Maria and Santa Maria Maddalena *ad Circulum*), which historically allowed the scholars to hypothesize the presence of the monument in this part of the city.

After the first fortuitous discoveries between the late nineteenth and early twentieth centuries, in 1937-38 Alberto De Capitani d'Arzago made a systematic and meticulous investigation into modern buildings and drew up a careful survey (Figure 3.5) of numerous and consistent sections of the circus foundations, of which most can no longer be identified [de Capitani d'Arzago 1939].

Since then, several discoveries and studies have added further information on the structure of the building without attempting a complete reconstruction. Several elements still remain to be identified, for example, access points to the building for the emperor and the public; the configuration of the carceres and the eastern tower, and the function of the apsidal structure identified by De Capitani D'Arzago on the western side, the appearance of the façade [de Capitani d'Arzago 1939]. Finally, there is still no data on the *spina* and the level of the track floor, the *arena*, not even identified in the latest surveys conducted in the circus area in via Vigna 6 and via Brisa 5 [Fedeli and Frontori 2020].

Figure 3.5. De Capitani's map of the circus indicating various information about the walls of the circus excavated or speculated.

3.2.2 Investigations: archival data and field inspections

The three-dimensional reconstruction of an ancient monument that no longer exists always represents a complex challenge that intrinsically requires a multidisciplinary approach. Technical, humanistic, and philological aspects must be considered and the final 3D model is often the result of an iterative process in which the various disciplinary components are compared to define the most possible reliable appearance. In this process, it is important that any possible clues, such as still existing remains, historical maps, archival photographs, and archaeological writes are properly researched and analyzed. The study of every possible documentary source is particularly important when the monumental complex is non-existent or there are very few remains, as in the case study reported here.

The ancient circus of Milan has, in fact, today almost totally disappeared. It has suffered the fate of many ancient buildings from the Roman era that existed in city areas: dismantled for the reuse of building materials, destroyed to make room for subsequent phases of urbanization, or hidden under newer buildings. The research work on the Circus, given the limited number of visible findings, began with in-depth philological research starting from historical and archival data that were collected and interpreted, by experts from different disciplines, to identify a reliable reconstruction of the monumental building.

The investigation was carried out drawing on all possible sources through bibliographic and cartographic research. In collaboration with the superintendency of Milan, it was possible to examine massively preserved archival materials such as photographs, protection decrees, and physical inspection diaries.

The main activities carried out are described in the following subsections:

Bibliographic research

One of the first steps was the bibliographic research to develop knowledge on the theme of Roman public buildings and specifically of circuses, which were built over a very long period of time and in different geographical areas. It was very important to study the examples of contemporary works, especially in the three-dimensional reconstruction phase to hypothesize and fill the information gaps related to the elevated development of the Milan circus. In this sense, a text of fundamental importance was the volume by an English scholar Humphrey, which reports an extensive study and many comparisons on the subject.

Furthermore, all the publications relating to the circus of Milan were consulted. Such publications report information on the studies and archaeological excavations carried out over time. Among these, the text of the archaeologist De Capitani was of fundamental importance. He was the first in the 1930s to conduct a methodical study on the monument, defining its position and general dimensions through special archaeological excavations. This study confirmed his hypotheses and disclosed the remains of parallel walls, some portion of the foundations, and a large part of the curve (Figure 3.5). Such remains are largely nonexistent or are invisible today.

Cartographic research

To understand the evolution of the vast urban area where the circus stood, cartographic research was also carried out at the Archivio delle Stampe Bertarelli in Milan. This archive kept a vast collection of maps. Hundreds of maps from various eras have been collected to trace the changes that have occurred over the centuries. Particularly interesting among the maps consulted is a 'wrong' map from the eighteenth century (Figure 3.6). In this map, the circus is positioned roughly correctly to the east of the city but with an inverted orientation, with the carceres to the south and the curve to the north. This gross representation error is significant for the reconstruction because it indicates that in the eighteenth century, although the memory of the monument was still alive, most of the physical monument must have disappeared.

Figure 3.6. An example of a historical map "1735, Mediolani, vi ante aenobarbi cladem extitit", the circus represented upside-down with respect to the real orientation is circled in red (courtesy of Archivio delle Stampe Bertarelli).

Photographic archives

The photographic archive at the Superintendence's office was also analyzed regarding the area of the circus. Among one thousand archival images, a hundred images were selected including artifacts visible during superintendent inspections or as construction project documentation (e.g. the subway, streets, and new buildings). These images are particularly relevant in several respects. In the case of still existing and visible remains, they allow the evaluation of the possible variation in the state of conservation of the artifacts. If the remains are no longer visible, as they are covered by modern buildings or have been permanently removed, the archival images provide precious documentary support for reconstruction hypotheses.

Figure 3.7. Photograph of the remains in via Brisa, during the excavation of a private buildings reconstruction in 1951, currently not visible. (Courtesy of Soprintendenza ABAP per le province di Co, Lc, Pv, So e Va).

Archaeological restrictions decrees

Several useful pieces of information were found in form of the documents related to the archaeological constraining decrees for the properties where archaeological remains were conserved. Such remains were documented through diaries, on-site sketches, technical data, and photographic surveys (Figure 3.8). This comprehensive set of information was particularly valuable because in the post-war period many buildings were demolished and rebuilt. The remains found during excavation were often documented and removed. For the construction of roads or public areas, the remains were covered, making them inaccessible. All the information collected was placed in a GIS (Geographic Information System) with the purpose of correctly linking them to specific locations in the area.

In addition to archival research, a thorough inspection was carried out in the field by visiting all the buildings and their basements within the area of the monument structures, with the permission of the superintendency and the collaboration of the residents. Through such visits, it was possible to evaluate the actual presence of remains, their state of conservation, and the opportunity to do a three-dimensional survey.

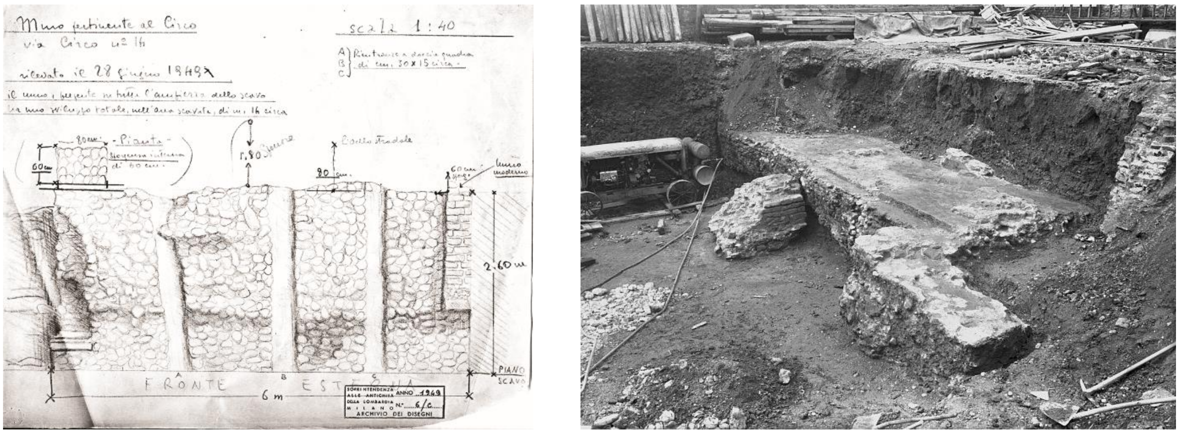


Figure 3.8. Drawing and photograph of an archaeological excavation carried out at via Circo 14 in 1949. These remains do not exist anymore. (courtesy of soprintendenza ABAP per le province di Co, Lc, Pv, So e Va).

3D survey and data geo-reference

Based on the described research, a survey campaign of all the visible remains of the circus area was carried out in order to obtain geometric, dimensional, and visual information about the single portions and their correct position in the geographical space. The final goal was to read all the data as a "single body" for analysis of the monument.

Figure 3.9. Mapping of the circus areas concerning the survey work.

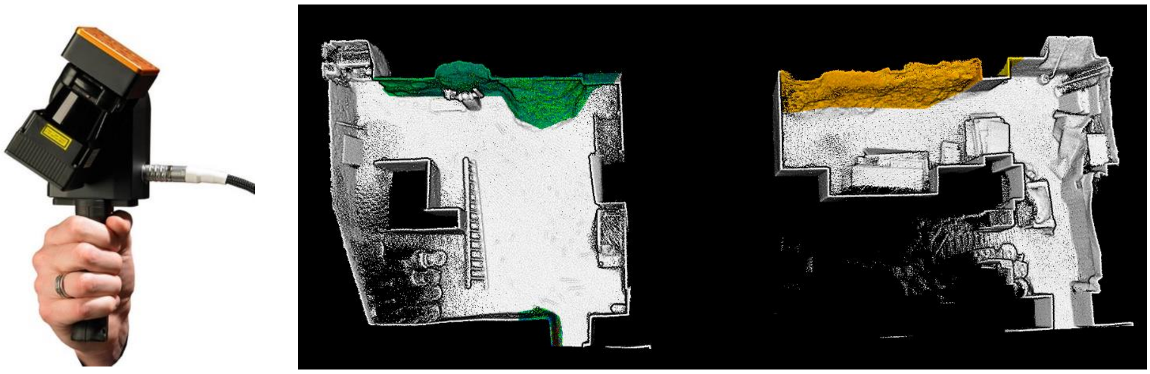
For this purpose, laser scanning and digital photogrammetry techniques were used to provide an accurate description of the remains by capturing millions of points with 3D coordinates and, in some cases, colors. Depending on the condition of the remains and the specific purpose of the survey, different technologies were used.

For the exterior parts, Time-of-Flight (TOF) or Phase Shift (PS) laser scanners were used to acquire the geometric and dimensional information of the remains, with a spatial resolution of at least 1 cm (Figure 3.10).

(a) (b)

Figure 3.10. Scanning the exterior parts of the concerning area: (a) use of a TOF laser scanning for exterior parts; (a) points cloud generated from TOF laser scanner.

For most of the inner parts and connections to the exterior, in order to have the needed data for georeferencing work, a hand-held mobile laser scanner was used. The 3D data were captured by simply walking through the area of interest, drastically reducing the time-consuming scanner set-ups and data registration associated with traditional terrestrial laser scanning methods (Figure 3.11).



(a) (b)

Figure 3.11. Scanning of the interior parts and connections with the exterior of the concerning area: (a) a handheld mobile laser scanner; (a) points cloud generated from the handheld laser scanner.

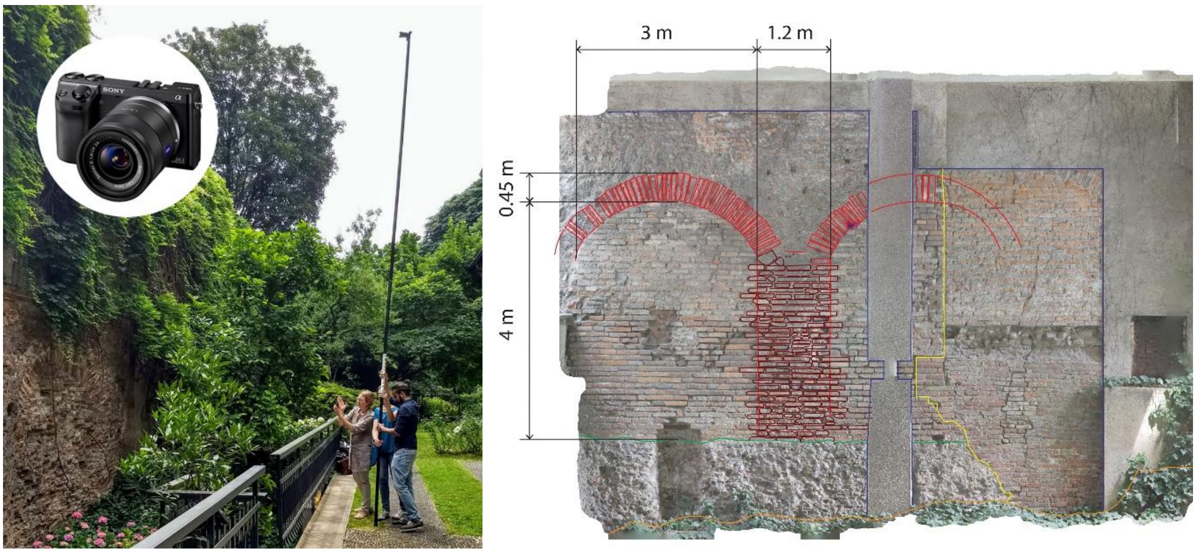
This aspect was relevant because of some particular aspects of the survey: (i) most remains are located in rooms and basements of private properties, often prestigious residences with issues related to privacy and security; (ii) long and complex paths to go from the indoor remains to the outdoor road position for georeferencing; (iii) the need of completing the work in a short time to remain as little as possible in the private residences during the data acquisition phase, and (iv) to minimize the post-processing time for generating the reconstructive hypothesis of the circus in time for the end of the project.

The survey was performed for the archaeological remains, the connection path from the remains to the outside, and a portion on the road for an extension of about 20 meters. Three-dimensional images were obtained from geometric surveys or point clouds with grey levels corresponding to laser reflectivity. The 3D point clouds of the acquired data were cleaned, aligned, and merged into a single georeferenced coordinate system.

Subsequently, the data were optimized and meshed in order to obtain a polygonal model usable for comparison with the data collected through photogrammetry and as a reference for reconstructing a 3D model of the monument.

The photogrammetric SfM/IM survey was performed only in some cases, where it was particularly important to enrich the geometric data with the color information of the texture to better read the wall traces. It was the case for example of the wall of Via Vigna/Via Morigi, where it is possible to analyze some structural issues and the stratigraphy of the monument (Figure 3.12)

The acquired photographs were elaborated with SFM/IM photogrammetric techniques to obtain a texturized 3D polygonal model. The models obtained from images were converged to the real scale by using metric targets placed on the scene and through a comparison with the polygonal model obtained from laser scanning.



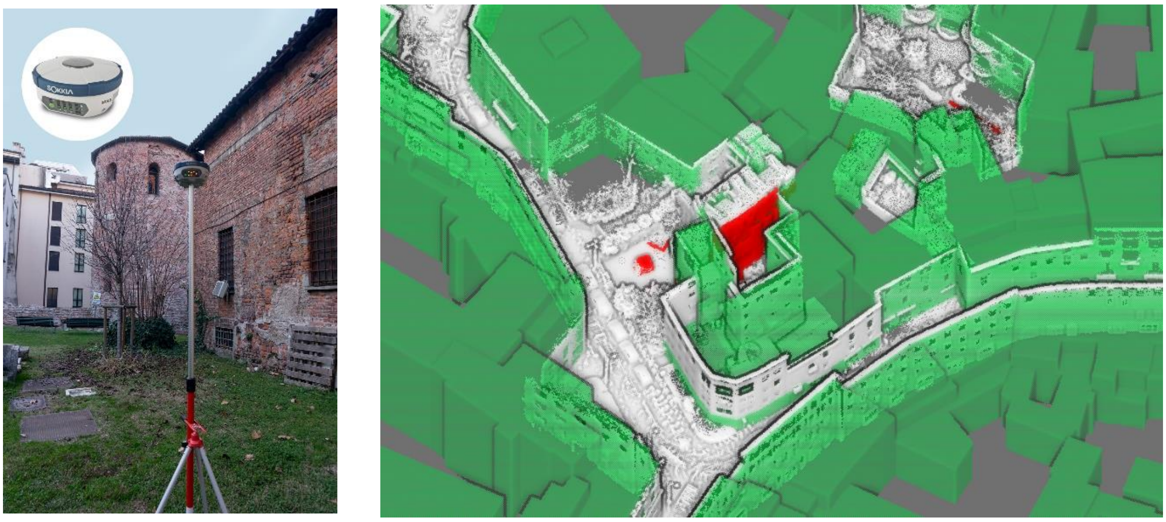
(a) (b)

Figure 3.12. The photogrammetric survey: (a) photo capturing of the circus remains for photogrammetry; (b) the textured orthophoto generated from the photogrammetric survey.

To place all the remains in the same georeferenced system, a topographic survey with differential GPS was performed using 13 natural points for the exterior part of each portion of surveyed remains.

This step was a crucial stage for generating a reliable starting point for the reconstruction, allowing to obtain georeferenced data and for correcting some information about the monument that remained uncertain after previous research. All the data needed for georeferencing the individual geometric surveys in a single reference system, coherent with the data of the Digital Terrain Model (DTM) provided by the Municipality of Milan, were extracted from the differential GPS-based survey (Figure 3.13).

The acquired data were reported in the geodatabase described above, in order to have an exhaustive mapping of information, and correctly referred to the geographical positions of the territory.



(a) (b)

Figure 3.13. (a) Topographic survey with differential GPS. (a) Differential GPS-based georeferenced acquired data.

3.2.3 3D digital reconstruction and 3D-4D digital exploration

The accurate reconstruction of the circus presented in this section is hypothesized by combining 3D surveys and field inspections of the actual remains still visible with historical maps, drawings, archaeological reports, and archived photographs. While the georeferenced 3D survey of the remains allowed to shed light on previously dubious aspects of the monument, the historical and archeological information was useful to hypothesize a reconstruction of the details which have been physically lost.

The most valuable hypothesis for the reconstruction of details is based on the archeological pieces of evidence from other late Roman circuses built in the same era (end of the 3rd and beginning of the 4th century A.D.). The five circuses that were built in that era were Nicomedia, Maxentius, Trier, Sirmium, and the circus at Constantinople. Among these constructions, the circus of Maxentius in Rome is the most completely excavated. It was built by the emperor Maxentius who was the son of Emperor Maximian (who most probably built the circus in Milan [Barnes 2013]). Therefore, most of the reconstruction of features, with no physical evidence left in the circus of Milan, was based on the excavated details of circus Maxentius in Rome. Other circuses built in earlier periods i.e. the circus at Lepcis Magna (one of the best-preserved Roman circuses) and circus Maximus in Rome, were also used as inspiration for the reconstruction of some details.

The reconstruction of such details was an iterative process i.e. at each step of reconstruction the hypothesis was revised by interdisciplinary researchers and professionals until reaching the most accurate assumption grounded in heterogeneous data.

Orientation of arena and walls

The style of construction of Roman circuses can be associated with the objective of Romans to make the chariot racing as fair as possible for all the competitors. The most important feature that became important in the design of Roman circuses was the distance between the starting gates and the near turning post. In different eras, Roman architects proposed several designs to allow all competitors to follow an equal path before starting the race and avoid accidents at the start of the race. In the late-Roman circuses, a solution that was adapted included the starting gates laid across a curve, inclined turning posts (and the barrier joining them) and changes in orientation in the walls of the circus on both sides [Humphrey 1986].

Until now, the inclination of the wall of the circus in Milan had been indicated with plausible, but not totally verified, angles. The integrated reading of 3D data of all the remains allowed the identification of the actual course of the walls that would result in an angle of 1° inwards on the eastern side, at Via Sant'Orsola, and a 3° angle towards the outside on the western side, at via Santa Valeria. The identification of these angles also allowed the hypotheses of the position of the start line and end line; which, according to the construction rules of the late Roman era, coincided with these changes of orientation of the walls.

All the mentioned elements can be found in the new plan of the monument (Figure 3.14). The plan was elaborated based on the position of the existing, detected, and georeferenced remains (in dark red) and taking into consideration all the bibliographic information collected during the project.

Figure 3.14. A new plan of the monument developed on the basis of the 3D scanning of the existing remains, accurately georeferenced with differential GPS, and taking into account all the documentary information collected during the project.

Length of arena and plan of the circus

The length of the arena proposed previously without the precise 3D data and geo-referencing was 485 meters. This hypothesis was made in the first half of the 20th century by considering the length of the arena of the circus in Milan same as that of the circus of Maxentius, which was already excavated at that time [de Capitani d'Arzago 1939]. But under the scope of this project, the analysis of the remains in elevation and some portions of foundations in the southern area made it possible to correctly identify the position of the curve, to calculate the actual length of 460 meters, inside the arena.

Apart from the length of the arena, by using the contemporary survey and geographical positioning technologies, not available at the time of previous studies, the investigation presented here is a systematization of a series of previous information. A comparison between the new proposed plan (in red) and the graphic elaboration proposed in the volume Images of Mediolanum, dated 2007 (in green), is demonstrated in Figure 3.15.

Figure 3.15. Comparison between the newly proposed plan (in red) and the graphic elaboration proposed by the most recent contribution in the literature, dated 2007 but based on previous approximate surveys (in green).

Once the plan was defined, the three-dimensional model of the circus was developed (Figure 3.16) considering all the data relative to the raised portions, the historical sources, and the comparison with other constructions of the same historical period.

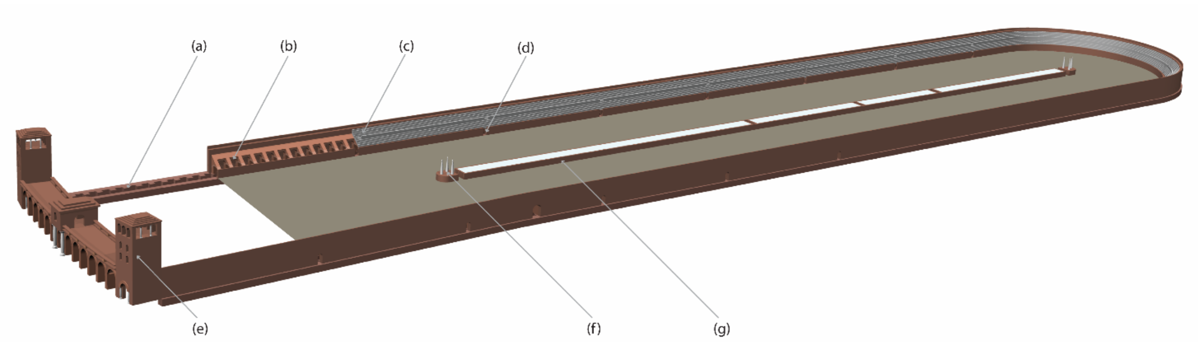


Figure 3.16. Three-dimensional model of the Roman circus of Milano with some sections to demonstrate important details: (a) basement, (b) internal and external walls with the vaults system sustaining the podium, gallery, (c) seating tiers, (d) access to the tribune, (e) tower of carceres, (f) cone of the meta, (g) barrier.

The peculiar elements of the reconstruction were evaluated by the archaeologists of the Civic Archaeological Museum and the Soprintendenza, who helped to identify the most reliable solutions.

Foundations and height of walls

The details of foundations were proposed based on a combination of actual measurements of the remains taken in the field at via Vigna 1, via Circo 10, via Cappuccio 21, and a previous survey of the remains in via S. Orsola n. 15 by Alberto de Capitani d'Arzago. The measurements taken during the previous complete excavations of the foundations were more reliable as it was not possible to survey the complete height width and depth of the foundation remains in the current situation. The inner face of the foundations was attached to pilasters that supported the arches of the vaults.

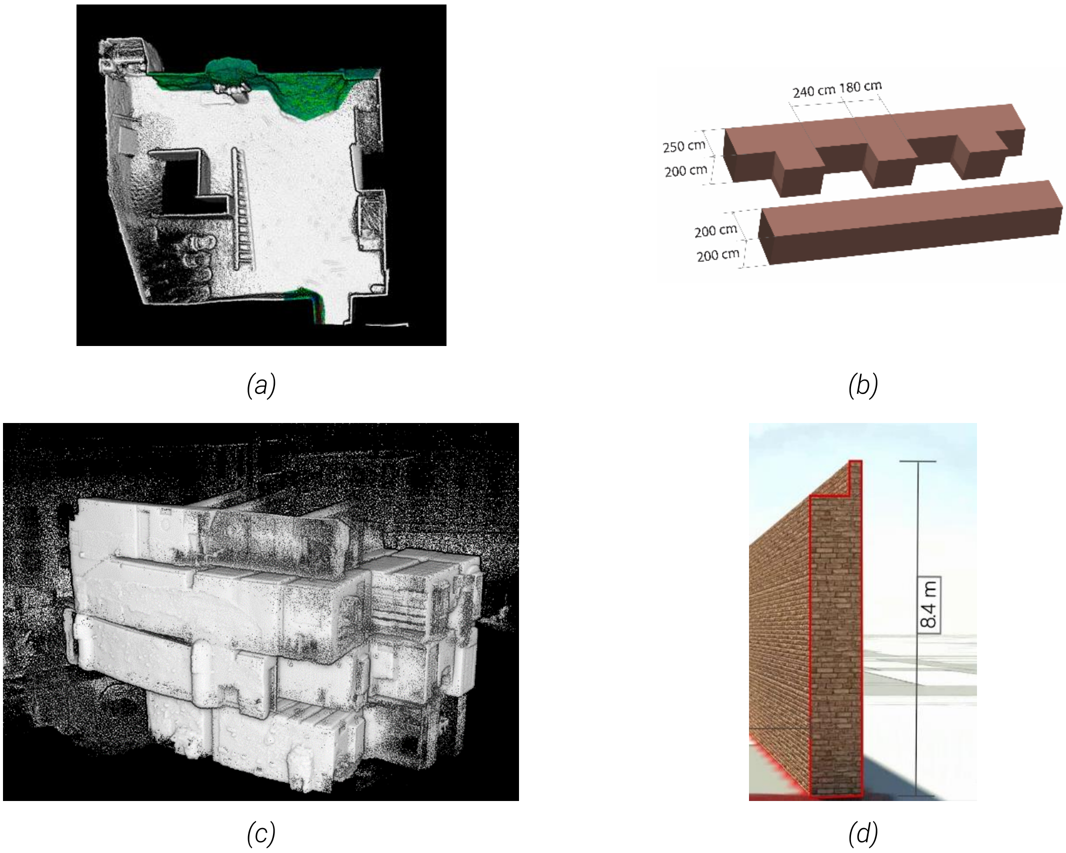


Figure 3.17. 3D data obtained from the remains of the circus and the reconstructed foundation and height of the wall: (a) 3D data of the foundation remains in via Cappuccio 21 with circus foundations highlighted in green; (b) reconstruction of the basement based on a 3D survey and previous excavations in via S. Orsola n. 15; (c) 3D data of the curved part of the circus wall still preserved in via Circo 9 which was used as a reference to verify the height of the external wall of the circus; (d) reconstruction of the exterior wall.

By analyzing all the areas in which it is possible to read the passage from the foundations to the masonry, the possible height of the arena floor has been identified. This results in having a greater share in the North and less in the South, consistently with the notions deriving from the bibliographic sources.

Similarly, the height of the exterior wall was also verified at the places where the whole height of the wall is still preserved. The measurements taken at the remains of the outer wall of the circus in via Vigna 1 resulted in 7m, which does not correspond to several other sources. Therefore, another measurement was taken at the curved end of the circus in via Circo 9, where the whole height of the exterior wall of the circus is preserved in a three-story building (Figure 3.17c). The measurements of laser scans at this point confirmed the total height of the circus to be 8.40 m.

Distance between the walls and detail of vaults

On the eastern side, at via Vigna 1, and on the western side, at via Cappuccio 21, it was possible to verify the distance between the external and internal walls. Specifically in via Vigna 1, the remains of external walls in the courtyard and the remains of foundations of the interior wall in the basement (fig. 12a) are still visible. By connecting the basement with the outdoors, the laser scanning survey of this area provided the precise distance between the remains outside and in the basement. Based on these measurements the width of the cavea was 4.75 meters (Figure 3.18b).

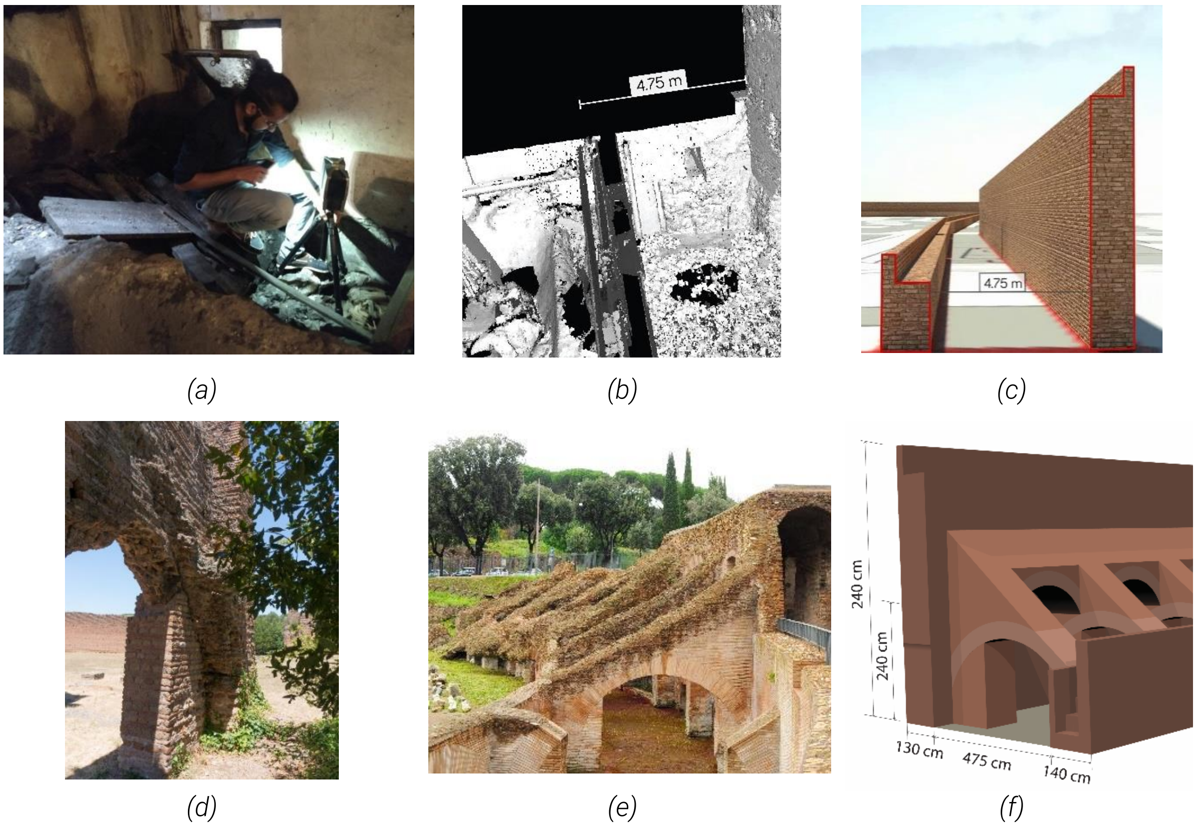


Figure 3.18. Data integration from various sources for the reconstruction of vaults: (a) Laser scanning in the basement of via Vigna 1; (b) point cloud generated from laser scanning to calculate the distance between the exterior and interior wall of the circus; (c) reconstruction of exterior and interior wall; (d) details of vaults in the remains of Maxentius circus in Rome; (e) details of vaults in the circus of Maximus in Rome.

The detail of the vaults that connect the outer wall with the inner wall was hypothesized by combining the 3D data through photogrammetry and studying other structures used for performance in the Roman empire. Besides providing support to the podium, the vaults in Roman circuses also served as a gallery for the public to access the seating tiers and exits from the circus.

The 3D model of the traces of arches and pillars in via Vigna 1, suggested that the outer wall of the circus was connected to segmental arches that were 3m wide and 4.45 m high from the foundations (Figure 3.18b). Apart from the details of arches, there are no other clues on the ground to reconstruct the exact structure of the vaults. The reconstruction hypothesis represented in figure 12f is a combination of studies of construction techniques used in the Roman period and comparing them with the limited physical pieces of evidence in the remains of the circus of Milan. The most likely structure consisted of vaults forming the ceiling of the corridor, intersected by architraves supporting the podium. The reconstruction hypothesis is a combination of 3D measurements of the circus remains in Milan with the design of vaults in the circus of Maxentius in Rome (Figure 3.18d) and the vaults structure still completely visible in the circus Maximus in Rome (Figure 3.18e). Even if the circus Maximus was built earlier than the Circus in Milan, it represents the best-conserved example to analyze and understand the Roman construction technique of performance buildings.

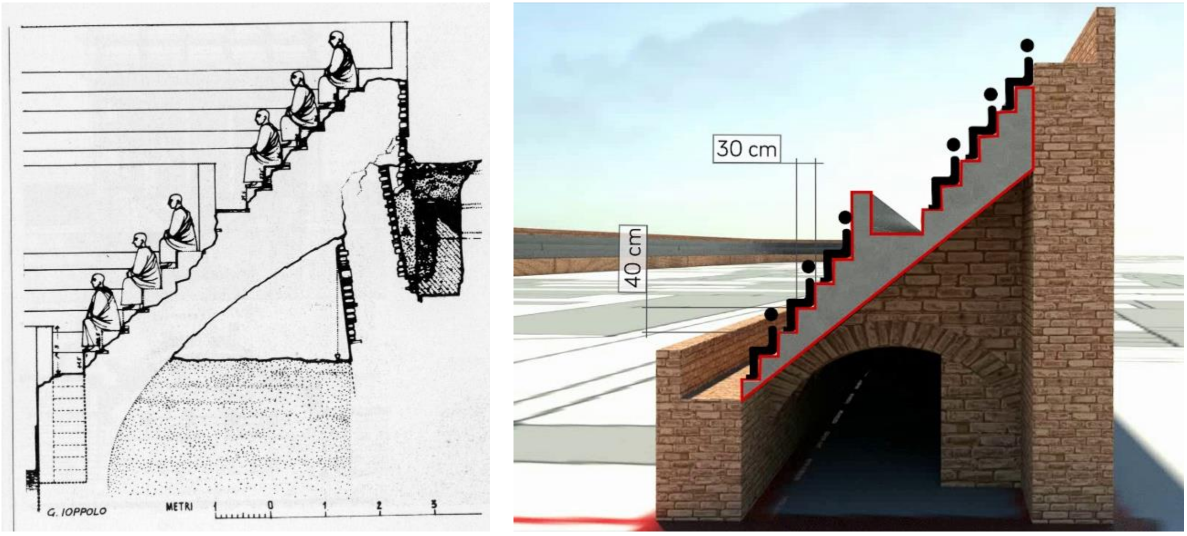
Due to the insufficient height of the interior wall remains, it was not possible to measure any details of the pillars supporting the podium. Therefore, the inclination of the podium support was also hypothesized by comparing it with other structures of the Roman era.

A comprehensive report on the reconstruction of vaults has already been reported in a previous publication [Guidi et al. 2017].

Design of seating

The precise measurement between the exterior and interior wall of the circus i.e. 4.75 m was combined with the inclination of 45° of seating tiers (according to the bibliographic sources in other circuses of the same period [Humphrey 1986]). Another aspect of the reconstruction of seating arrangement is the subdivision of seating tiers into two different parts based on the social classes as suggested in the literature [Roberti 1984]. Another clue for such an arrangement comes from the reconstruction of seating tiers of the circus of Maxentius proposed by Giovanni Ioppolo (Figure 3.19)[Ioppolo 1988].

These past studies, combined with the measurements of remains, led to the hypothesis of the probable design of seating tiers with two classes of three seats, with 30 cm width for seating, 30 cm width for the feet, and 40 cm height for each step (Figure 3.19b). A comprehensive report on the reconstruction of seating tiers has also been reported in a previous publication [Guidi et al. 2017].



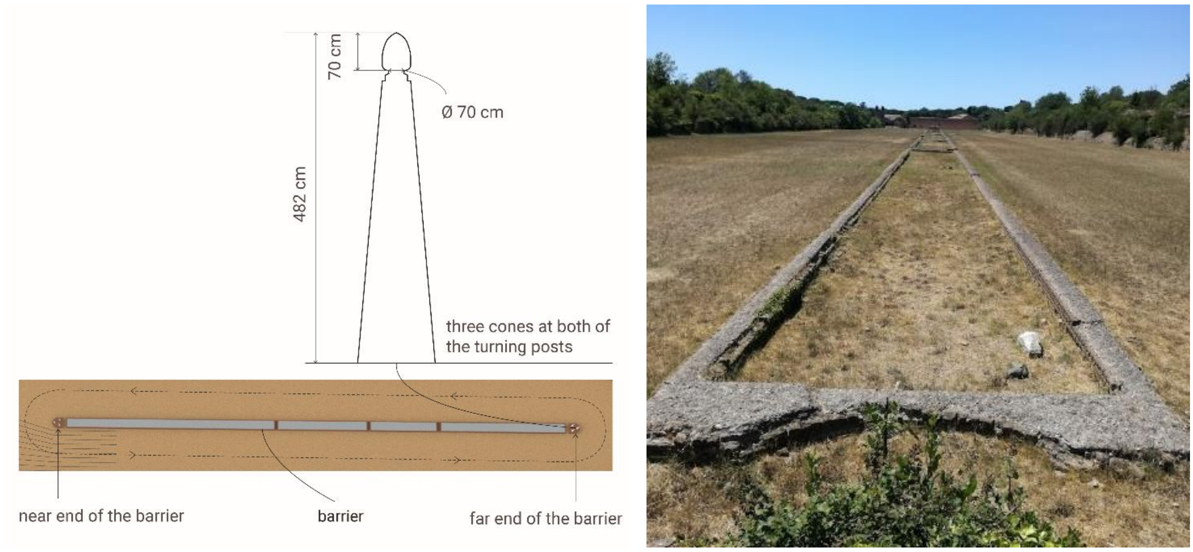
(a) (b)

Figure 3.19. Seating design in Roman circuses: (a) reconstruction of seating tiers of the circus of Maxentius proposed by Giovanni Ioppolo; (b) Reconstruction hypothesis of seating tiers in the circus of Milan.

Barrier (Spina)

A typical feature of Roman circuses was a dividing barrier called spina, which connected the turning post at the far end with the turning post at the near end. It was composed of a succession of pools of water. Its axis was typically inclined in relation to the axis of the circus. Through such inclination the distance to be traveled by each competitor to the near post was equal and the competitors in the outside stalls did not need to make sharp turns to come inside the barrier. The turning posts at each end of the barrier were also used as a foundation of three massive cones, which were traditionally placed above the barriers [Humphrey 1986]. The barrier was usually the first element of the arena to be built.

However, no remains of a barrier are still found in the circus of Milan, but analysis of other Roman circuses reveals that a barrier with pools of water and turning posts were an essential component of any Circus in the Roman era. Therefore, the Roman circus in Milan most likely had the same features, which have not been excavated. The reconstruction layout of the barrier, turning post and the cones represented in Figure 3.22a is a combination of design of such details in the circus of Lepcis Magna and circus Maxentius. The reason behind hypothesizing the details based on Lepcis Magna is that it has the best-preserved barrier of any Roman circus, therefore it provides a complete picture of the original appearance of barriers in Roman circuses. The four water basins of the barrier were instead inspired by the circus Maxentius, where the foundations of the barrier are still visible (Figure 3.22a).

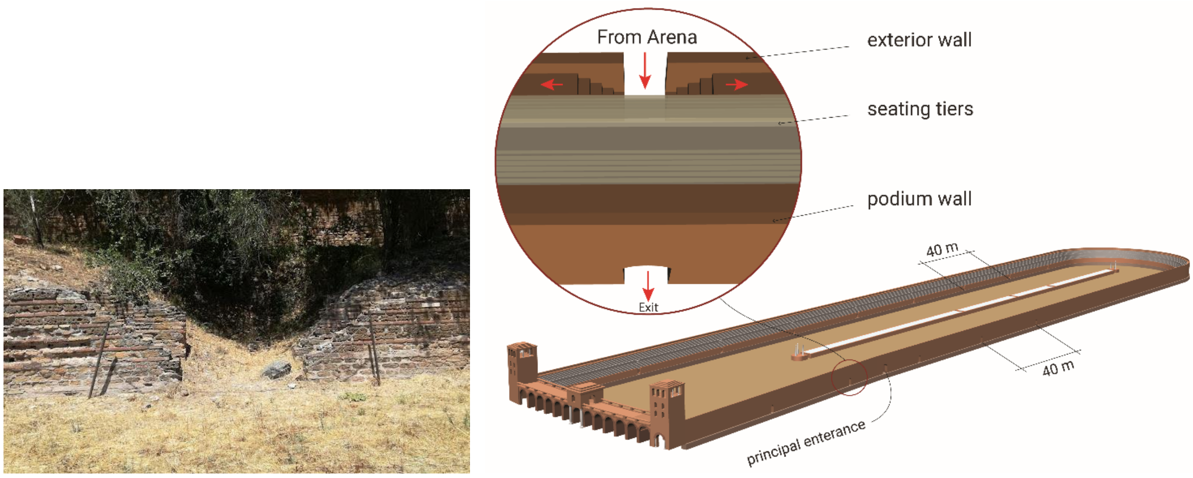


(a) (b)

Figure 3.20. The reconstruction hypothesis of the barrier, turning posts, and cones: (a) probable orientation of barrier with respect to the arena and details of cones on the turning posts based on the remains of Lepcis Magna; (b) remains of barrier in circus Maxentius.

Access to the tribune and stairway

There were several entrances and exits at regular distances for the spectator in a typical Roman circus as it is still visible in the circus of Lepcis Magna and circus Maxentius (fig. 16a). The galleries under the tribune were accessible through these entrances and exits. They also provided access to the doors to the arena and the stairways to the tribune. There was also a principal entrance usually near the starting line through which the chariots passed at the end of each race.



(a) (b)

Figure 3.21. The reconstruction hypothesis of access to the tribune and stairway: (a) remains of circus Maxentius; (b) reconstruction hypothesis for circus in Milan.

The reconstruction hypothesis for the access to the tribune and stairway (Figure 3.21b) is based on the design of such details still visible in the circus Maxentius and the circus of Lepcis Magna. The accesses at regular intervals of 40m with a principal entrance near the starting line hypothesized in this reconstruction are based on the actual measurements taken at the remains of circus Maxentius in Rome.

Textured 3D model

Once the phase of definition of the planimetric, volumetric, and structural aspects was completed, a texturing phase was carried out with the attribution of hypothetical materials to the various surfaces. Unfortunately, neither the sources nor the realized acquisition allowed the description of the original materials with certainty, so the mappings of materials are intended to create only a suggestion of the original appearance of the circus.

Figure 3.22. Rendering of the proposed reconstruction of the Roman circus in Milan.

In addition to the model of the circus, further 3D elaborations have been realized to perceive the evolution over time of the investigated area. The depicted zone related to the imperial era has been enlarged to illustrate the extent of the Maximianus defensive walls, the main roadways, and waterways.

A representation of the pre-imperial era has been made of the same area, which reveals the urban impact of the circus-palace complex. For the construction of the circus, the path of the walls and that of the river Piccolo Seveso were diverted towards the west.

Moreover, a three-dimensional textured model of the area in the contemporary era was realized to allow, through 3D-4D digital exploration, to acquire an awareness of the enormous evolution of the area over the centuries. All 3D representations, which define the variations in time of the studied area, are visible on the project website (https://cht2.eu/index.php/online-visualization) that allowing the visitors to interact with 4D (3D plus time) urban landscapes through a common Web browser.

Through this tool, it is possible to explore maps, display specific layers for individual historical periods and enrich the experience with information elements associated with hot spots on the model.

3.3 PERVIVAL Project: Design of digital interaction for complex museum collections

In the last two decades, the use of digital applications has had exponential growth in all areas of science, production, and daily life. The context of cultural heritage is no exception in this sense, both related to the study, diagnostics, and restoration of the artworks and related to the exhibition.

Museums are increasingly making use of multimedia applications and technological devices to enhance the traditional roles, such as classification, archiving, collection, exhibiting [Parry 2013b], capturing the visitors' attention, and enhancing the global comprehension of cultural heritage aspects.

Various technologies, belonging to the so-called Mixed Reality (MR), allow the visitor to explore the exhibition contents moving from the real world to the virtual one with different degrees of immersivity [Milgram et al. 1995], improving the cultural learning opportunities [Bekele and Champion 2019; Petrelli 2019]. Thanks to multiple devices and technologies, adaptable inside or outside the museum, nowadays it is potentially possible to integrate the complementary information delivered through engaging narratives into the exhibition.

Since the beginning of the 2000s, the concept of intangible cultural heritage (ICH), made explicit by the 2003 UNESCO convention,[12] has commonly become part of the debate related to the safeguarding and dissemination of culture. Subsequently, the dichotomy between tangible and intangible was overcome, considering that any cultural real asset represents an entity that carries links to the socio-cultural, economic, and religious context in which it was created and used. The semantic relationships between different objects can, therefore, represent important keys for defining museum collections and appropriate exhibition narratives [Kirshenblatt-Gimblett 2004; Micoli et al. 2020].

When there is a collection composed of physical items strictly interlinked by many semantic connections associated also to ICH components, eventually non-explicit, we can call it a Complex Museum Collection (CMC) [Micoli et al. 2020]. It's true for many ancient objects related to religious rituals whose meaning is very difficult to be explained and understood if they are observed out of context.

In the case of CMCs, it would not be easy to bring the meaning of both single items and the whole collection to the public with traditional exhibition means such as written and drawn panels. Digital approaches and tools, in their several forms, represent effective support for museum scope to reveal the embedded complexity between items. For example, virtual models, multimedia supports, and hyperlinks can be useful to deliver specific information not explicitly deductible by the items alone. Digital tools can also be used to realize narrative content for effectively making the articulated connections among the CMC objects understandable to visitors.

The case study presented in this section is related to a specific set of ancient Egyptian artifacts such as mummies, coffins, amulets, vases, and the book of death papyrus associated with symbols, divinities, and magic spells linked together through the articulated funerary ritual typical of that civilization. The analyzed digital interactive application refers specifically to the ancient Egyptian collection of the Civic Archaeological Museum of Milan and has been developed

[12] The United Nations Educational, Scientific and Cultural Organization. Convention for the Safeguarding of the Intangible Cultural Heritage; Paris, France, 2003.

under the PERVIVAL project —Virtual Paths for the Improvement of Complex Museum Collections in the Milan Area (http://www.pervival.polimi.it/)—over a two-year timespan (2018–2020).

The PERVIVAL application and its technological implementation have been designed to satisfy various needs related to the specific museum context, which is however representative of a widespread Italian and European museum reality. Among the aspects taken into consideration, it is worth mentioning the need to:

- maintain a low cost during the creation and maintenance of the installation
- limit the use of physical space
- avoid assembly of people for a long time
- avoid sound to not disturb other visitors
- obtain a tool suitable for a broad range of end-users, avoiding a "technological divide" effect by including also people with little or no technological skill

Considering all these aspects to host the interactive application a touch-screen kiosk [Burmistrov 2015] was chosen, more easily accessible in terms of implementation and user interaction, rather than immersive technologies.

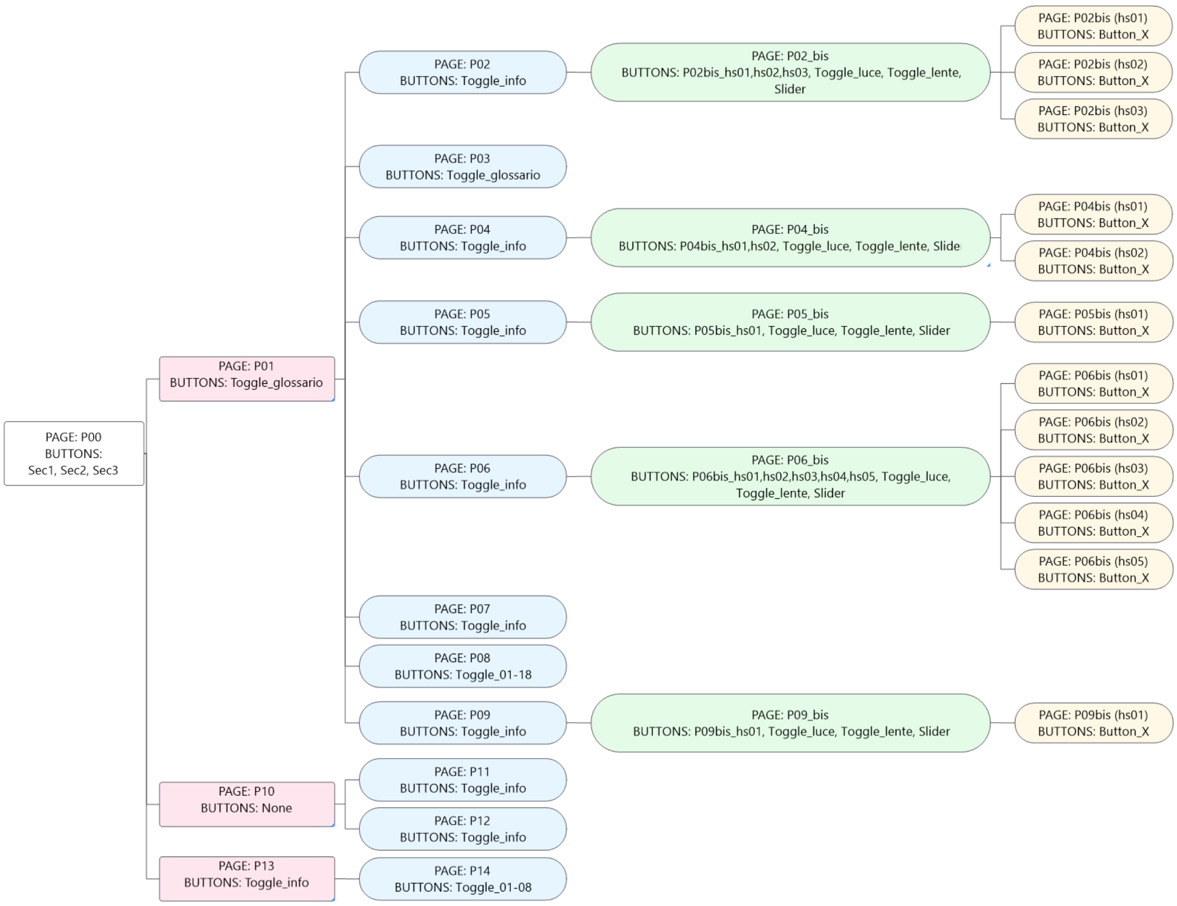
The development of the application, as suggested in the literature [Katifori et al. 2018], involved an interdisciplinary team composed of experts in digitalization, computer graphics, virtual reality, museum curators, Egyptologists, and anthropologists working together with an iterative process [Mason 2015] to realize an authoring workflow for interactive storytelling in a cultural heritage context.

The work approach was to link the exhibited physical object through the immaterial elements with the challenge to create a synthesis able to reveal the appropriate meaning of both a single object and the multiple connections related to the complex collection. The core narration chosen for the virtual application was the ancient Egyptian funerary rituals related to the passage of the deceased from life to the Afterlife.

To communicate this archaeological knowledge into an engaging narrative [Roussou 2001], a subset of grave goods from the entire collection belonging to the museum was chosen, digitized, and used in the virtual application to create a rich visual content supported by reliable historical references.

The virtual interactive application, developed with the platform Unity3D, is based on a treemap with three main ramifications, related to the essential conditions for achieving eternal life according to the beliefs of the ancient Egyptians [Redford 2005; Scalf and Lowry 2017; Pinch 2004; Andrews 1994; Stewart 1995; Lise 1979; Miatello 2018]:

- preserve the intact body through mummification, coffin, sarcophagus, and an appropriate tomb
- feed the defunct with real or represented food
- face ordeals with the help of rituals, amulets, and coffin decorations as described in the papyrus of the "Book of the Dead" that was part of the burial goods



LEVEL	I	II	III	IV
CONTENT	Main section description	Main item description	3D interaction	Item's in-depth content(s)
ACCESS	direct or through predefined path	direct or through predefined path	through predefined path	hotspot selection in level III page

Figure 3.23. Hierarchy of different pages in PERVIVAL application. The names of unique buttons on each page are specified as recorded in the log data.[13]

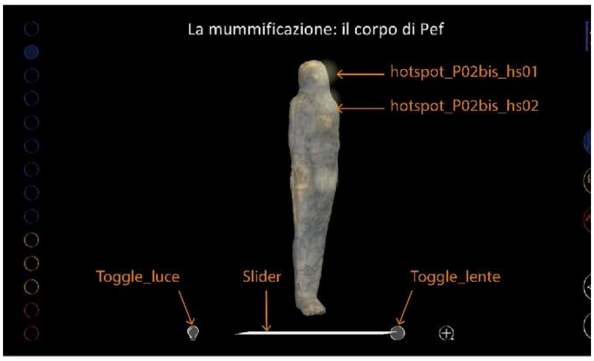
All the elements and pages belonging to one of the main ramifications is distinguishable thanks to the explicit graphic language adopted based on color and logos.

The navigation of the app could be guided by the predefined path suggested by the authors for non-expert users. For more expert users an option of free navigation was provided, with the possibility to choose a single object/content to explore.

The application has been hierarchically structured into four levels corresponding to a growing deepening of the contents and different interaction modalities. Hereafter, the main characteristics of the four levels are reported.

[13] Some of the button names are in Italian language: glossario = glossary; luce = brightness; lente = lens.

(a)



(b)

(c)

Figure 3.24. Examples of buttons on different pages of the PERVIVAL application: (a) the standard buttons on level II pages; (b) standard buttons on level III pages; (c) exit button on the level IV pages.[14]

Level I - Contains a synthetic description of the main sections, by text and an iconic image of the theme; it is accessible both via direct icon selection and through the predefined path.

Level II – Contains single or multiple items textual description associated with other different media that, according to the importance that the items have within the collection, can be: small 3D animation; image-scroll panel, or static image representation with access to the following level of the app. This level is also accessible via direct icon selection or through the predefined navigation path.

Level III – Contains the 3D interaction related to the most important pieces of the collection. By accessing the page a 3D model animation, based on the real object survey, is shown. Once this is completed, the user can interact with the item through three graphic elements: i) a slider, allowing to review and stop at a specific perspective of the 3D model animation; ii) a magnifying glass to zoom on a specific point the 3D model and observe the chosen area in detail; iii) one or more

[14] Some of the button names are in Italian language: avanti = forward; indietro = back.

hotspot point, giving access to pages of IV level with an in-depth description of contents linked to the 3D model selected point. This level is accessible only through the predefined path, from the corresponding page on Level II.

Level IV – contains details about the single object, each specific topic presented with different media such as video or drawings. This level IV is accessible by selecting the hotspot connected to the 3D model on the Level III page.

The application could be navigated with different approaches according to the expertise of the users and time at their disposal, following the predefined path or choosing the content to be explored. In terms of time, two extreme ways to navigate were proposed corresponding to the minimum and maximum required time: 3 minutes for a synthetic overview of the whole material of the three main themes at the level I, and twenty to twenty-five minutes for complete navigation of all contents at all levels.

3.4 Last supper interactive - LSI project: Storytelling through virtual reality application

The Last super interactive (LSI) project is a Virtual Reality application that combines experimental digital narratives and virtual storytelling with immersive technologies and is based on the Last Supper, a late 15th-century mural painting by Leonardo da Vinci located in the refectory of the Convent of Santa Maria delle Grazie in Milan. This project explores the effectiveness of creating 3D replicas of cultural heritage for creating virtual narratives. LSI application allows the audience to visit the painting from multiple viewpoints and perspectives to gain a better understanding of how the linear perspective was used and applied by Leonardo in the painting. The accurate representation of the 2D painting in form of a virtual 3D model enables visitors to virtually transfer inside the painting. The visitors can not only visit "Cenacolo", the room where the painting is located but can also learn about the historical context of the painting through the connected story of the surrounding environments where Leonardo created this masterpiece (Figure 3.25). The surrounding environment of the cenacle room was created by meticulously digitizing in 3D and optimizing a Laser scanning survey from outside and inside of the architectural complex of the Dominican monastery of Santa Maria delle Grazie. A photogrammetric project was also developed and integrated with 3D scans for improving the visualization of the church exteriors. Several laser scans were then collected to capture the details of the interiors of the monastery and connected cloister. This scanned data set was then aligned with the exterior point cloud of the monastery. This sort of survey was carried out for the first time for the monastery by the Department of Mechanics of Politecnico di Milano, allowing the reconstruction of the original path from the square to the interior of the church, to the cloister, and finally to the cenacle room. Furthermore, this application shows the emotional aspects of digital storytelling techniques, both for individual visitors and groups. The realistic 3D models created by integrating photogrammetry and laser scan allow connecting the virtual narratives of this project to the physical environment containing Leonardo's masterpiece and the virtual representation of space given by the painting.

by two means: (a) VR headsets and (b) 3D glasses with a projection on the wall and floor of an exhibition hall.[15] By using these 3D technologies, the users could have an experience of visiting and exploring a place even if it is far away from them in reality.

[15] https://ars.electronica.art/center/en/exhibitions/deepspace/

A detailed explanation of the project development, user interaction modalities, and storytelling methods can be found in [Fischnaller 2018].

(a) (b)

Figure 3.25. Snapshots of the LSI application: (a) at a point where the user is virtually standing outside of the room containing the masterpiece "the last supper" and the connected church of Santa Maria delle Grazie in Milan Italy; (b) in the "cenacle room" where the visitors can learn about the painting by projecting perspective lines over it.

4. QUALITY OF REALITY-BASED 3D DIGITIZATION OF CULTURAL HERITAGE: QUANTITATIVE METHODOLOGY

The virtual or physical interaction between the end-user (stakeholders of this research) and a digitized heritage asset or its physical replica, depends on the credibility of its digital representation. Therefore, the quality of a 3D model is critical and must be kept under strict control.

Photogrammetry[16] is widely used for the digitization of museum content because it has several advantages over the active scanning devices:

- the process of automatic photogrammetry is much faster than the active scanning process, specifically when the goal is to produce a large amount of 3D models in less time [Fassi et al. 2013b; Gonizzi Barsanti et al. 2013]
- the range maps produced as a result of active scanning generally produce a significant amount of geometric artifacts (especially when the surfaces have abrupt reflectance changes on texturized objects), which requires manual elimination in the post-processing step with a risk of losing important details in the 3D model
- some materials largely used in CH objects such as marble, opaque glass, and painted objects are less optically cooperative with the laser than digital photography
- the pipeline to create a textured 3D model from 3D scanning requires a substantial amount of manual work for alignment of range images, mesh editing, and texturing of mesh [Bernardini and Rushmeier 2002b].

Even though the photogrammetric process is highly automatic, the results can still be affected by: (i) the photographic quality of the images, which depends on the settings and features of the photographic camera, and (ii) the proper distribution of camera locations in 3D space around the artifact being surveyed. Furthermore, working in the difficult situations of the museum environments present several challenges. To deal with these challenges, several guidelines for efficiently digitizing the museum contents through photogrammetry were developed at this step.

This chapter identifies best practices for effective 3D digitization of CH assets in museums and metrological guidelines for optimal accuracy of reality-based 3D models. The resulting material can then be converted to create interactions between users and CH assets for different experiences as described in the previous chapter.

Part of the contents of this chapter is the subject of two papers discussed in an international context [Malik and Guidi 2018; Guidi et al. 2020a]. The test case, for optimizing the 3D digitization process in museum environments, is the massive 3D digitization project of the Uffizi Gallery in Florence, Italy [Guidi et al. 2018]. The metrological guidelines such as optimal overlap between consecutive images in automatic photogrammetry are provided based on laboratory tests.

[16] See [Luhmann et al. 2006] for details on close range photogrammetric process.

4.1 The process optimization

This section describes a methodology for efficient massive 3D digitization of ancient sculptures under the scope of the IU-Uffizi project. During the massive digitization of CH assets in this project, a variety of different issues were experienced in the museum, including working with different lighting conditions, the placements of sculptures at difficult places for shooting images, inaccessible heights, and different ways for posing camera on the scene in an environment where the use of drones is prohibited. To solve such issues, specific technical choices were made to reduce the digitization time and costs while maintaining a high coherence between the physical artifact and its digital counterpart. These technical solutions are discussed here, in a context where the purpose is to massively digitize complex objects in their original setting by minimizing the impact on the museum. Furthermore, the metadata collection and organization before digitizing the museum objects and a methodology for quickly scaling the digitized 3D models without physical targets have also been discussed in this section.

4.1.1 Working conditions

Digitizing the artifacts in a museum without closing it to the public means adopting the technological choices, as much as possible, according to the situation. The position of the CH objects in the exhibition environment, in many cases, might be very unsuitable for shooting images all around them for photogrammetry. This is particularly true for a museum such as the Uffizi Gallery, where the number of pieces being displayed are enormous, and the space available for the exhibition is relatively limited. As a result, many important objects are located close to the walls or at high places like the example shown in Figure 4.1

(a) (b)

Figure 4.1. Examples of sculptures placed in difficult positions for image capturing: (a) A sculpture close to the wall in Uffizi gallery; (b) large sculptures placed at height in “Loggia dei Lanzi” in Florence

Objects close to walls

In the cases when the objects to be photographed are near to the wall, a possible solution could be to physically move the artifact to the middle of the room to allow a proper photographic shooting all around. But relocating such objects is not an easy task, both for their weight, ranging from hundreds to thousands of kilograms, and for their intrinsic value, which makes it mandatory to use the extraordinarily costly and time-consuming processes and precautions.

By analyzing the current situation of the objects in the Uffizi gallery museum located close to the wall, it was found that 90% were at about 20cm from the wall. Such space allows entering behind the sculpture with a small camera like the one being used in this project, even if with the lens at a very short distance from the sculpted surface. This implies a limited field of view and consequently the need of covering the surface with thousands of images. Also, the zone behind an object is usually very dark and operating without any additional lighting would have required increasing the ISO setting and opening the diaphragm. But this would have grown the image grain and reduced the depth of field, which is exactly the opposite of what a shooting from a short distance would need.

(a) (b) (c)

Figure 4.2. The solution adopted for digitizing the objects near the wall in the IU-Uffizi project: (a) HVL-RL1 LED ring light with attachments for different sizes of lenses; (b) configuration of the camera tested in the lab before its use in the museum; (c) shooting the backside of a sculpture in the museum with ring light attachment.

The solution adopted was to use a wide-angle lens suitable to focus at a very short distance from the surface (18 cm), coupled with a ring illuminator with continuous light (Figure 4.2). This light is designed for video recording, therefore, it provides continuous illumination in contrast with a flash. The continuous illumination feature ensures the proper functionality of the autofocus during the collection of the image set even from the darker areas of the scenery and normalizes the illumination conditions on every shot. Although using a light attached to the camera can be questionable in photogrammetry owing to the actual change of mutual object-light orientation for each shot which might affect the appearance of each feature over the surface of the surveyed object, previous experimental work demonstrated that for small displacements of the point of view such influence is negligible.

This configuration was first tested in the lab on a test object to find the optimal balance between light intensity, shooting time, and aperture, suitable to capture at that distance with the most limited blurring. By using this combination of wide-angle lens and illumination, it was possible to capture the back surfaces of the sculptures near to the wall also in very dark areas, which was not possible otherwise.

(a) (b)

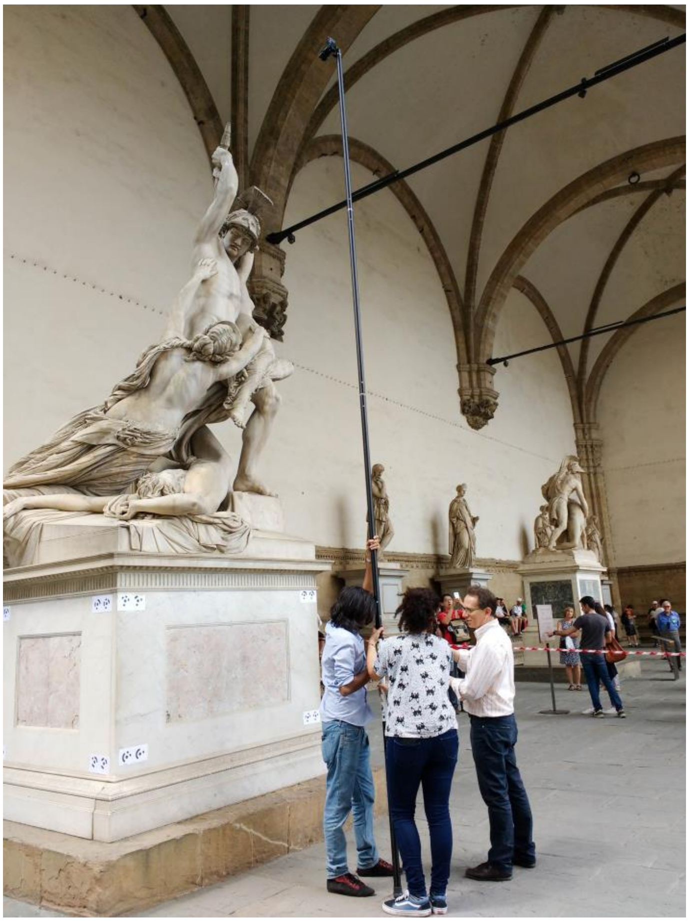
Figure 4.3. 3D digitized model of a sculpture close to the wall: (a) model obtained with a 24mm lens, where a huge lacking part is present; (b) model obtained with the 12 mm lens and the ring illuminator, completed in all areas close to the wall.

Camera positioning in high places

Carrying out a photogrammetric project on large artifacts, like those owned by Uffizi gallery (up to 3m high), requires the movement of the camera all around the object and therefore also in positions not easy to reach. Two different approaches are usually used to reach higher places for a photogrammetric survey: climbing up the scaffoldings all around the artifact to be digitized or using a drone.

The first approach, generally used for restorations of the statues, involves a lot of additional work for mounting the structure of the scaffolding and for moving it around the object resulting in a solution too slow and costly especially for a systematic digitization process involving many pieces. The drone is instead problematic regarding the related flight authorizations in the city center of many cities. The strict regulations about unmanned flying vehicles in the Italian art cities, where the areas hosting the sculptures are visited by hundreds of tourists every day, prevent the authorities to allow any flight unless the area is closed to the public. And this condition was not practical to be reached unless a huge amount of time would have been spent in dealing with the associated bureaucratic issues. Therefore, for the IU-Uffizi project, none of the two approaches were followed. The simplest solution was to use a tall monopod on top of which the camera was mounted.

(a)



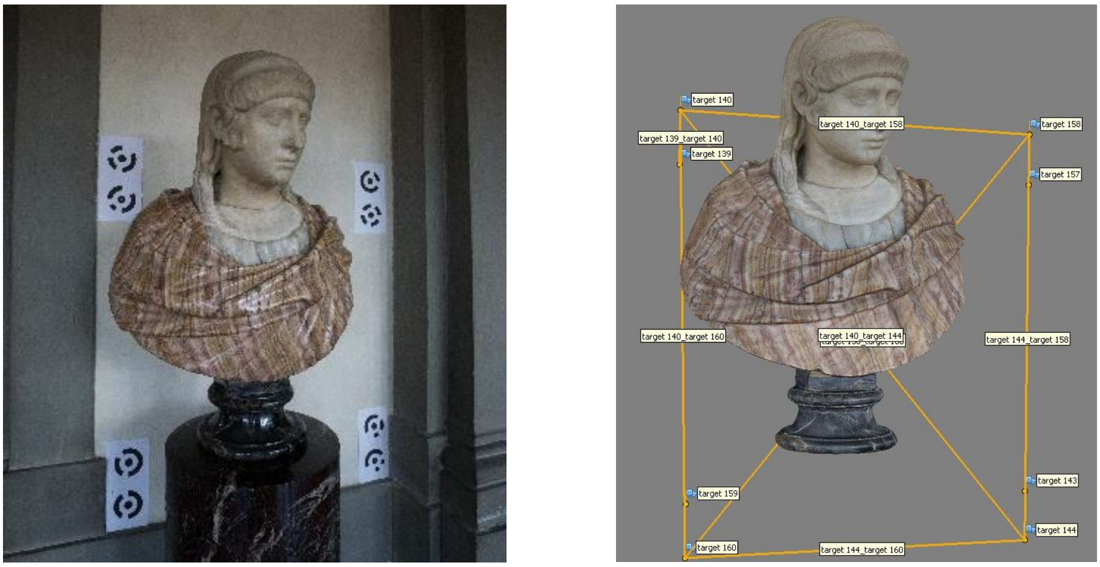
(b)

Figure 4.4. Monopod for the shooting of tall sculptures in IU-Uffizi project: (a) four-section structure of the monopod; b) operating conditions with two people holding steady the pole and one operator showing the movements to do for obtaining the optimal framing.

The camera used for this purpose has a feature to be remotely controlled with a portable device like a smartphone or a tablet. Both the viewfinder and all the photographic controls can be transferred to a handheld device, and an operator can remotely decide to expose, focus and shoot. This specific monopod is an 8m aluminum pole made of 4 sections of 2m each, which can be used modularly for reaching 2, 4, 6, or 8m of height (Figure 4.4a). It was remarkably suitable for the gigantic sculptures in the "Loggia dei Lanzi," in front of the Uffizi gallery (Figure 4.4b) and for a part of the Uffizi collection. Such statues are from 2 to 3 meters high, and lie on a 1.5 to 2m basement, reaching easily 4 to 5 meters of absolute height from the floor. Imaging these artifacts from 8m allows capturing all the details of the top surfaces that would be otherwise lost. In addition, reducing the height at steps of 2m allows for capturing images all around the sculpture from different heights. Even though this method requires extra personnel, at least one person for holding the pole and one for capturing images remotely, but the overall time of the survey is much more less than using other methods.

4.1.2 Scaling of digitized model

The digital 3D models produced as a result of the photogrammetric process do not have an absolute scale by default, therefore the 3D measurements must be scaled to metric values after their elaboration. In the initial stages of the IU-Uffizi project, scaling has been done by following the standard procedure of photogrammetry, i.e. by placing several targets in space around the object to be digitized (Figure 4.5).



(a) (b)

Figure 4.5. Distance-based scaling: a) placement of physical targets in space around the sculpture to be digitized; b) detecting the same markers in the virtual environment and applying values to the scale bars as measured in reality.

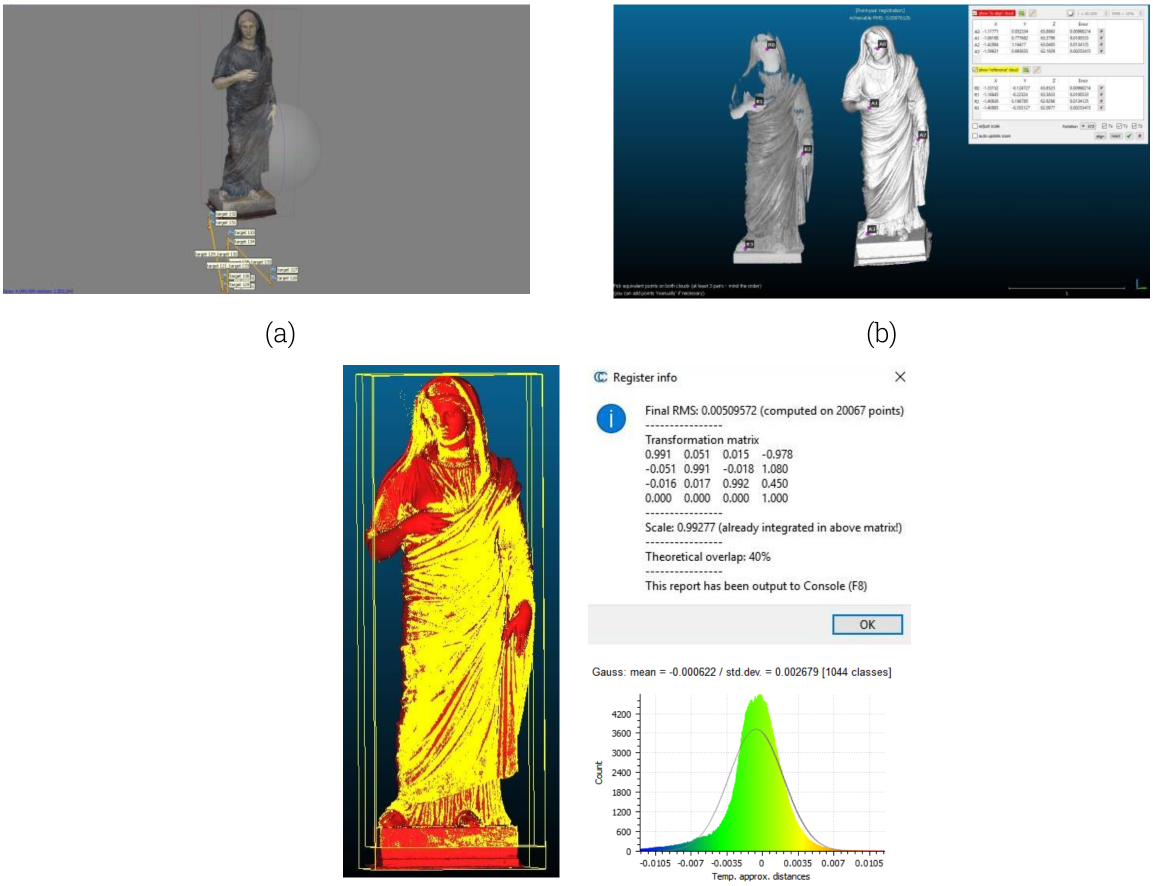
The distances between these targets in space are measured in advance, and after image matching, these targets are detected on several photos from different points of view in order to locate their position in the virtual space. The distances between virtually identified targets are given the same values measured during the photogrammetric survey. Hence the 3D model is scaled accordingly. Even though accurate scaling can be achieved by utilizing this method, the process is very time-consuming in terms of placing the targets in the scene and manually measuring precise distances between them.

As an alternative in the IU-Uffizi project, to speed up the scaling procedure, a FARO Focus 3D laser scanner[17], working on the principle of range sensing based on phase-shift detection, was used. As

[17] https://www.faro.com/it-IT/Products/Hardware/Focus-Laser-Scanners

the points cloud generated by a laser scanner has an absolute scale: each point represents the actual position of the corresponding point in space with some measurement uncertainty, the model generated by the photogrammetric process (which has a relative scale) can be scaled by aligning it with the points cloud from laser scanning.

To demonstrate the accuracy of this method of scaling, a 2m tall sculpture of Demeter was digitized by photogrammetry and scaled by using physical targets, which resulted in a scaling error of less than 0.5mm (Figure 4.6a).



(c)

Figure 4.6. Comparison of different scaling procedures: a) 3D mesh of a sculpture of Demeter generated by Agisoft Photoscan[18] and scaled by detected targets and applying the measured values in reality to the virtual scale bars. The scaling error is 0.5mm in this case; b) Imported points cloud and mesh of the Sculpture of Demeter in CloudCloud: captured by the laser scanner on the left and generated and scaled in Agisoft on the right; c) Aligned and scaled mesh with reference to the point cloud from the laser scanner, demonstrating final scaling results and error histogram.

Correspondingly, a single scan was made for a part of the same sculpture (front part in this case) by the laser scanner mentioned above. The polygonal mesh generated and scaled by the standard

[18] https://www.agisoft.com/

procedure was then imported into CloudCompare[19] (an open-source 3D point cloud processing software) along with the point cloud of the front part of the sculpture generated by the laser scanner (Figure 4.6b). The mesh was then aligned and scaled with reference to the point cloud by using an iterative closest point (ICP) algorithm, which resulted in a scaling error of less than 1% of the polygonal mesh, which represents the closeness of sizes after scaling by traditional procedure and scaling by the method described here (Figure 4.6c).

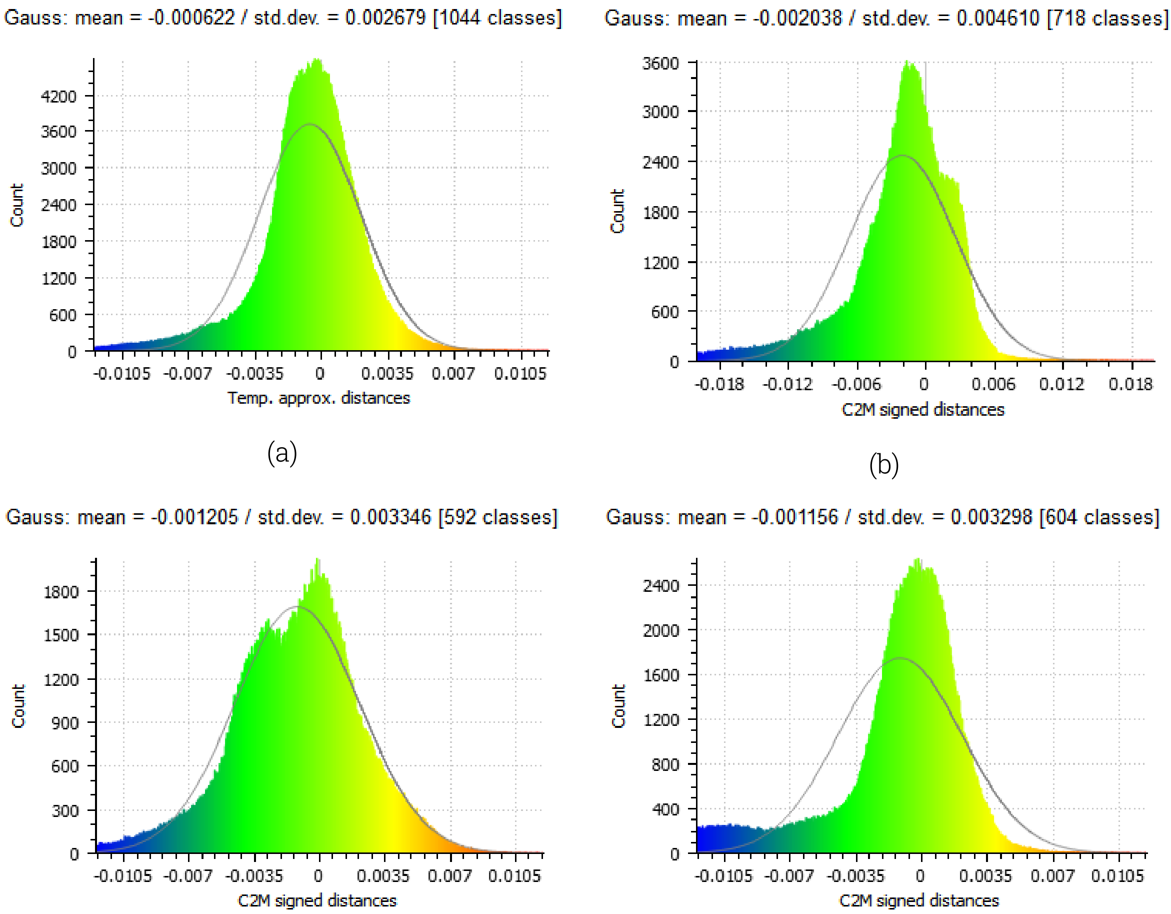
A standard deviation of error of 2.68mm was observed when the distance between the aligned mesh and the points cloud was computed. A part of this error is due to the error associated with the photogrammetric model (set up to be less than 0.5 mm in this case). The remaining error is directly related to the measurement uncertainty of the laser scanner whose theoretical ranging uncertainty is 2 mm on calibrated targets.

In this case, the material characteristics of the sculpture (marble) tend to increase such uncertainty [El-Hakim et al. 2008a; Guidi et al. 2009b], making the actual observed standard deviation of error reasonable. However, this local uncertainty does not affect the overall scaling, which is done on the whole shape of the sculpture.

More tests were performed with the same procedure on different objects of varying sizes and surface qualities: (i) sculpture of Demeter (2m tall with dark rough marble surface);[20] (ii) sculpture of She-wolf (1m long with maroon shiny marble surface);[21] bust of Vespasian (0.9 m high with partially shiny white marble surface);[22] and (iii) bust of Domitia (0.8 m high with rough white marble surface).[23] The scaling and alignment errors are compiled in the form of histograms in Figure 4.7 and Table 4.1.

It can clearly be seen in the results that scaling of models by the traditional method and the method described here, resulted in almost same output in all of the cases. It can also be noted that the standard deviation of error between the scaled model and points cloud from the laser scanner, is solely dependent on the surface quality and measurement uncertainty, as it is highest in the case of the sculpture with the shiniest surface (She-Wolf) and least in the case of the sculpture with the roughest surface (Demeter). On the other hand, the scaling error is maximum for the tallest sculpture and minimum for the smallest sculpture. Hence, it can be concluded that the scaling error is independent of the quality of the laser scan but depends on the whole shape and size of the sculpture.

[19] https://www.danielgm.net/cc/
[20] http://www.digitalsculpture.org/florence/main/model/702d9e44070048abb99ac8c714f49765
[21] http://www.digitalsculpture.org/florence/main/model/f3b0490b2c674cf9be20951ffa2dda0c
[22] http://www.digitalsculpture.org/florence/main/model/7649922359c946bc8015b12abd370c44
[23] http://www.digitalsculpture.org/florence/main/model/ac188b45242f471489838480ff948044



(c) (d)

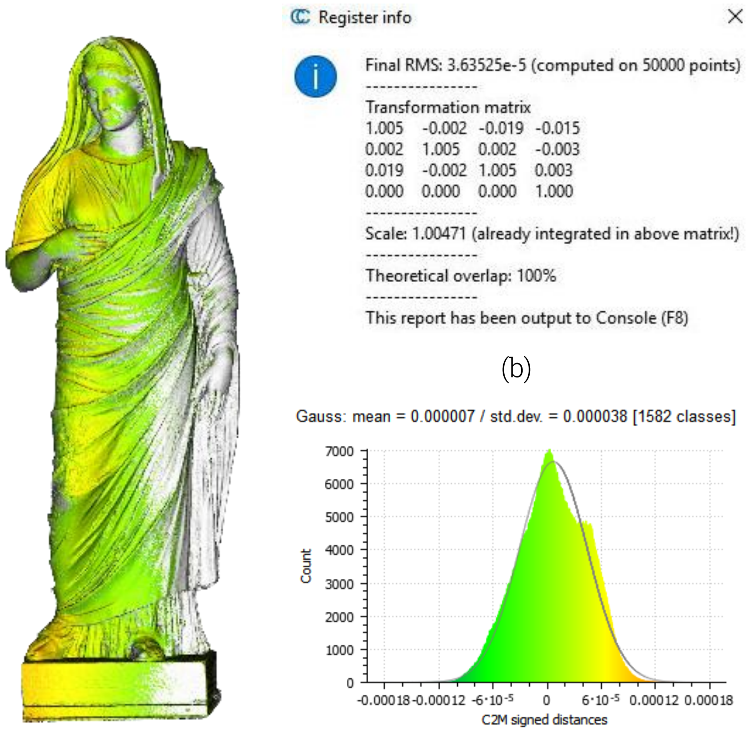
Figure 4.7. Histograms of errors after distance computation between the scaled models and the points cloud from laser scanner for different sculptures; (a) Demeter; (b) She Wolf; (c) Bust of Vespasian; (d) Bust of Domitia.

Table 4.1. Scaling errors and standard deviation of error after distance computation between the scaled models and the points cloud from laser scanner for different sculptures.

	Scaling error (%)	Standard deviation (mm)
Demeter	0.72	2.68
She Wolf	0.50	4.61
Bust of Vespasian	0.22	3.34
Bust of Domitia	0.18	3.30

The results demonstrated in Figure 4.8, confirm that the scaling of models by the traditional method and the method described here, resulted in the almost same output (less than 1% of difference) in all of the examples demonstrated here. Therefore, it is opportune to use the approach of scaling photogrammetric models with laser scanning to save time in placing physical targets and measuring their relative position during the photogrammetric survey.

Even though this method requires the availability of more equipment on-site, the data suitable for the following scaling step are represented by a single laser scan image taken from a few meters from the sculpture, which in terms of time takes much less than preparing the targets network around the object and measuring all the relative distances needed for the traditional scaling phase.



(a) (c)

Figure 4.8. Results in Cloud Compare after aligning and scaling the model scaled with physical targets with the model scaled with a laser scan: (a) residual errors color-mapped on the model; (b) numerical output of the alignment revealing a scaling factor of 1.00471; (c) histogram of the comparison residuals.

4.1.3 Metadata collection and organization

The final question of the photogrammetric survey is related to storing the digital model within a repository, implying the collection of the metadata associated with the object that the 3D model represents. In the context of an articulated project, where hundreds of objects have to be digitized, the metadata collection should not be separated from the acquisition of the images for generating the 3D model.

(a) (b)

Figure 4.9. Metadata collection examples: (a) Two museum objects (Monumental crater and Nymph with panther) in the Uffizi gallery prepared for the photogrammetric phase; (b) closing images of the respective dataset, reporting the inventory number and the title of the artifact.

For this reason, an acquisition protocol involving the acquisition of a closing image for each object was defined in the IU-Uffizi project. Such images represented the label of the sculpture in the museum, reporting the title of the statue and its inventory number, like the one shown in Figure 4.9. The latter represents a first hooking point that allows connecting this brief piece of information with a more articulated record conserved in the official catalog of the Museum. Published in the 1950s and progressively updated in the years by specialists, this archive reports all the data regarding the known history of each artifact, from which it was possible to extract the proper descriptive metadata associated with each model [Mansuelli 1958]. The metadata in this way was not created from scratch, which would have involved an additional effort not sustainable for the project, but generated starting from a pre-existing controlled source, as seen in previous projects documented in the literature [Guidi et al. 2013].

The final piece of information was related to the collection of the technical data associated with the 3D digitization, including the camera model, the lens, the software used for the photogrammetric processing and the mesh editing, and other technical details reported in Table 4.2.

Table 4.2. Metadata collected for each 3D model under the scope of the IU-Uffizi project.

Object Metadata	Photo Paradata	Model Paradata
Identifiers	Camera Body	Photogrammetry
Unique record #	Model	Aligned photos
Title/Name	Serial#	Tie points
Uffizi inventory #	Resolution	Reprojection error
Description	White Balance	Matching mode
Basic description	Color temperature	Dense cloud size
Characteristics	ISO	Meshing mode
Format	Lens	Raw mesh size
Authors	Model	Texture size
Date	Serial#	Targets STD (mm)
Materials	Aperture	Phogrammetrist
Inscription	Photo acquisition	Processing date
Dimensions	Average GSD (mm)	Modeling
Provenience	File Range	SW program (s)
Surface appearance	Number of Photos	Interventions
References	Photographer name	Mesh size
Physical location	Shooting date	Major Errata
Link to bibliography	Photo processing	Name of Modeler
Rights	Software used	Date of Modeling
Recording	Major Edits	
Notetaker	Link to edits PDF	
Date of document	Lens Correction	
Access constraints	Processor name	
Transcriber name	Processing date	
Transcription date		

4.2 Optimal lateral displacement in close-range photogrammetry for CH

Based on the use of automatic photogrammetry different researchers have made evident that the level of overlap between adjacent photographs directly affects the uncertainty of the 3D dense cloud originated by the SfM/IM process. This section investigates if, in the case of a convergent shooting typical of close-range photogrammetry, an optimal lateral displacement of the camera for minimizing the 3D data uncertainty can be identified.

4.2.1 Background

Automatic photogrammetry based on SfM/IM has been a game-changer in many fields where 3D digitization is needed. The fields of application are very different, ranging – just to cite a few - from industrial applications [Luhmann 2010], deformation monitoring of structures and bridges [Taşçi 2015], forestry assessment [Iglhaut et al. 2019], forensics [Villa and Jacobsen 2019], medicine [Ey-Chmielewska et al. 2015], zooarchaeology [Evin et al. 2016], paleontology [Fau et al. 2016], special effects for cinema [Collet et al. 2015], and CH documentation [Aicardi et al. 2018].

Specifically, in the case of CH documentation, photogrammetry has been particularly beneficial for the simplicity of the 3D acquisition and modeling process, the relatively low cost of the associated equipment compared to dedicated technologies like 3D laser scanners, and the possibility to extract both shape and texture of an object/scene from the same set of images. Those features involve a shortening of the time for creating a 3D model from the survey data that can be several times shorter than using an active device, allowing a consequent reduction of costs, particularly critical in a low-budget context as that of digital cultural heritage.

For these reasons, SfM/IM has been the methodology that has made possible the various initiatives of massive 3D digitization in museums [Guidi et al. 2018; Guidi et al. 2015b; Hess et al. 2016; Santos et al. 2014] and heritage sites [Gruen et al. 2003; Guidi et al. 2009c; Georgopoulos 2018; Kasapakis et al. 2018] that paved the way for broad digital access to heritage information otherwise impossible to gather without a physical visit to the heritage venue in question.

Camera orientation factors affecting photogrammetric 3D data in general

In all these fields, it has been demonstrated that the quality of the captured 3D data in terms of measurement errors is related to the Ground Sampling Distance (GSD). This term originated in the Remote Sensing domain, with specific reference to aerial photogrammetry, where the target is quasi-planar, and the camera sensor plane is parallel to the target. The GSD is intended as the spacing between two adjacent pixels projected over the target surface [Driggers 2003], and for that reason remains constant in any area of the image. In close-range photogrammetry, especially when performed on cultural heritage artifacts such as sculptures, vases, and other museum objects, the target surface can be very far from a plane, therefore the projection of the sensor's pixel grid over the target gives a variable GSD with a minimum at the minimal target-camera distance. In any case, according to the literature, the smaller the GSD, the smaller the error.

In addition to this factor, the literature also reports the influence of the so-called baseline/distance ratio. In other words, when several images with the same GSD aim at the same feature from two different points of view, the measurement error affecting the estimation of the feature's 3D coordinates also depends on the ratio between the displacement of the observation points (i.e., the baseline) and their average distance from the feature.

According to this view, considering a coordinate system centered in one of the two cameras where x and y identify the plane of the sensor and z the optical axis, we can express the standard deviation of error along z as [Luhmann et al. 2014]:

$$\boldsymbol{\sigma_z = \frac{h^2}{b \cdot c}\sigma_p} \tag{1}$$

where the meaning of the parameters is:

h = average distance between the two cameras and the feature;

b = baseline;

c = principal distance (i.e., the focal length of the lens plus an additional shift to achieve sharp focus);

σ_p = error affecting the estimation of the point over the camera image plane.

According to this relationship, fixing all the other parameters, the larger the baseline, the lower will be the error. But it is also clear that the larger the baseline, the more difficult will be the identification of the feature on the two projections. Therefore, by distancing the two points of view too far the result will be an increase in uncertainty in the positioning of the same feature on two different projections. And this increased uncertainty on the plane of the sensor will then be projected in the 3D space involving an increase of uncertainty in the estimation of the feature's 3D coordinates.

These two opposite requirements led in the '90s to the definition of the so-called 3x3 rules for simple photogrammetric documentation of architecture [Waldhäusl and Ogleby 1994], updated in 2013 [Waldhäusl et al. 2013] and adopted as a guideline by the "International Committee of Architectural Photogrammetry" (CIPA). According to these rules, the optimal baseline/distance ratio in the normal case (i.e., optical axes of the camera parallel to each other) ranges from 1:4 to 1:15 and from 1:1 to 1:15 in the convergent case. In any case the minimal suggested image overlap is 60%. The reason that the overlap and the baseline/distance ratio are mentioned as separate issues is that lenses with different focal length give different angles of view, providing also different overlap between adjacent shots in correspondence of the same baseline/distance ratio.

The book by Luhmann et al. mentioned above [Luhmann et al. 2014] presents the same relationship (1) with a different formulation, trying to make evident the separate influence of the scale of the objects in the photogram and the mutual inclination of the cameras:

$$\boldsymbol{\sigma_z = q \cdot m \cdot \sigma_p} \tag{2}$$

Where:

q = h/b represents the distance/baseline ratio or "design factor", associated with the angle between the two lines of sight (i.e., the reciprocal of the baseline/distance ratio mentioned above);

m = h/c represents the magnification factor, a different way of indicating the scale of the object on the photogram. Once the number of megapixels featuring the sensor is available, this is the same kind of information provided by the GSD in aerial photogrammetry.

According to this source, "practical values for the design factor q vary between 0.4–0.8 for excellent imaging configurations" in the case of convergent shooting all around the object. No numerical correspondence is associated with the idea of "excellent;" however, it is reasonable to interpret this as a configuration leading to the minimization of measurement uncertainty. In any case, these configurations, lead to values below 1.0, indicating a baseline larger than the average distance of the camera from the target, which is extreme in terms of possible changes of the feature once projected over the sensor plane by so many distant points of view.

By using the reciprocal of the numbers provided by the CIPA 3x3 rules, we can see that in this case, the optimal q would range from 1 to 15, representing a much lower inclination of the camera's lines of sight with respect to the "excellent imaging configurations" suggested by [Luhmann et al. 2014]. In this case, the baseline ranges from a value equal to the average distance of the camera from the target (q=1) to a value much smaller than that (q=15), in any case with a span of more than one order of magnitude.

In both cases, the aspect related to the recognizability of the feature on the image is not raised. This is instead a crucial point that deserves to be better analyzed.

Camera orientation factors affecting specifically SfM/IM 3D data

When we move from traditional to automatic photogrammetry, identifying corresponding points on different images is no longer a manual activity. What makes the photogrammetric process automatic in SfM/IM is using a procedure that extracts a set of features from each image that allows the more likely features to be identified without the intervention of a human operator. Algorithms such as the "Scale Invariant Feature Transform" (SIFT) [Lowe 1999], its approximated version "Speed up Robust Feature" (SURF) [Bay et al. 2006], the low complexity "Binary Robust Independent Elementary Features" (BRIEF) [Calonder et al. 2010], or similar ones, are capable of associating an identifier based on local luminance gradients with each group of pixels emerging from the background for their luminance contrast. This makes it possible to identify the same feature on different views of the same scene. Being associated with parameters that are not necessarily univocal in the image, such correspondence is usually refined by algorithms that estimate the camera roto-translation from one position to another, determined as the mean pose estimation associated with the globality of the corresponding features, and identify which of the correspondences is too far from such behavior. The latter process is carried out by algorithms conceived for identifying outliers from a set of observed data such as "Random sample consensus" (RANSAC) [Fischler and Bolles 1981], its evolution MLESAC [Torr and Zisserman 2000], or other similar outlier removal processes [Zhou et al. 2017]. Several authors have demonstrated that this phase works better if the lateral displacement among images is lower than that afforded in the manual case because this maximizes the recognizability of correspondences. Once the set of corresponding features among two or more images is reliable, a bundle adjustment process makes it possible to calculate precisely the exterior orientations of the different camera positions and the interior orientation of the camera used for the shooting consisting of principal point coordinates, principal distance and the various distortion parameters (radial, affine and tangential).

However, it is the last phase of the process, the IM, that plays a major role in determining the measurement uncertainty overlapped on 3D data. In this phase image patches of any oriented image are matched with the most likely patches of a corresponding image along the epipolar lines. Such a process may work on couples of images if stereo matching is implemented [Tippetts et al. 2016], or several other images in the case of multi-view stereo matching (MVS) [Furukawa and Ponce 2009]. This way of systematically extracting the dense cloud from the images affects the criteria for evaluating the optimal camera distribution in space, because the smaller the lateral displacement, the more similar will be the related projections of the same scene, and consequently the matching process will be more accurate. Conversely, for large lateral displacements, the images will be more different from each other, and the more probable will be a wrong matching, increasing the probability of a wrong 3D estimation of the associated point. This result, when extended to a population of millions of points, will involve a general increase of 3D uncertainty overlapped over the actual 3D data [Hu and Mordohai 2012].

Previous works on optimal camera orientation in SfM/IM photogrammetry

The presence of two opposed requirements—one for maintaining a low distance/baseline ratio q for making the orientation of different cameras more robust, the other for achieving a high q to maximize the SfM/IM process performance, requires to search for a compromise that, at least for close-range photogrammetry, has never before been quantitatively analyzed.

In the literature, different works mostly applying to aerial photogrammetry from drones can be found, where the images are mainly nadiral (i.e., with the cameras' optical axes orthogonal to the terrain and parallel each other), where the effects of lateral displacement for a given focal length is evaluated globally in terms of image overlap. According to a traditional vision, the overlap between adjacent images in the aerial strips is set to 60% as forward overlap (along-track), while the overlap between adjacent images between strips is set to 20% as side overlap (across-track) [Wolf and Dewitt 2000; Lemmens 2011]. However, Haala and Rothermel in 2012 [Haala and Rothermel 2012], analyzing a UAV survey by nadiral images taken with a zoom camera Canon Ixus 100 IS with the minimal zoom setting (f=5.9 mm) at a height of about 115 m (GSD=30 mm), tried to experiment larger overlap values. The overlap was 75% in the flight direction and 70% among adjacent flight lines. The considerable overlap and image redundancy allowed a very efficient elimination of erroneous matches improving the reliability of the 3D point cloud.

Such an outcome has been further detailed by research in the field of forest canopy survey, showing in 2015 a comparison between LiDAR and photogrammetric 3D data of the same forest obtained applying SfM/IM with different conditions of altitude and overlap [Dandois et al. 2015]. The LiDAR data were used as ground truth and the 3D clouds obtained with photogrammetry were compared against them. The Root Mean Square (RMS) error of the 3D data deviation from the reference was used as an index for estimating the measurement uncertainty of each photogrammetric setup. One of the photo sets was produced by a drone equipped with a Canon ELPH 520 HS, flying at a fixed height of 80m (GSD=33.6 mm), with different overlap levels. The paper's results show the uncertainty level that progressively decreases from 7m to 1m corresponding to overlaps ranging from 60% to 96%. Considering the camera and lens reported we can estimate that the 60% overlap provides q=1.9, while the 90% case gives q=19.4, a design factor very far from the theoretical optimal values.

A deeper exploration of this point appeared in 2018 by Ni et al. [Ni et al. 2018], again in a study oriented to the survey of vegetation from drone images. In that case, a Sony NEX 5T was used on a drone flying at about 300m from the ground using the wider angle supported by the camera's standard zoom lens (f=16mm), implying a GSD=86 mm. In this case, 79 images were taken choosing a baseline among adjacent shots (29 m) in such a way that 10% could be added to the previous image along the flight direction. The image overlap of the raw data set was therefore high (90%) but could be reduced in steps of 10% by leaving out an appropriate number of images in the set. For example, leaving out one image every two shots reduced the overlap from 90% to 80%; if two shots were omitted, the overlap was reduced to 70%, etc. Even though the purpose of this study was to determine the average accuracy of the forest canopy estimation, one of the incidental results shows the RMS error of the photogrammetric data against the LiDAR reference at variable overlap levels. These results make evident a decrease of RMS error for smaller overlaps with a re-growth of the RMS error at the maximum overlap. This suggests a possible worsening of the process when the overlap is too high, but also an optimal value for overlap levels much higher than the traditional 60%. This general data is confirmed by a recent review study about photogrammetry of forests, stating that an optimal image overlap should be in general >80% [Iglhaut et al. 2019].

Another paper exploring the effects of image overlap over the photogrammetric 3D data quality, also published in 2018, refers again to measurements in the field of vegetation assessment [Zhou et al. 2018]. In contrast to the papers cited above, this study was based on a scaled experimental setup made to produce a stronger control of the camera positioning. This makes the arrangement closer to the close-range configuration than the required analysis in this research. The experimental set-up consisted of a structure (7.3 m × 1.7 m) built by two sets of aluminum sliding tracks, positioned horizontally above the text field. A camera holder attached to the structure was moved through timing belts by two stepper motors on the xy plane. The movement along the longer structure dimension simulated the flight direction, while the other movement made it possible to generate different image stripes parallel to each other. Three test objects were used: a parallelepiped (73 mm x 48 mm x 98 mm), a cylinder, and a mushroom-shaped object consisting of a hemisphere lying on a cylinder. The two latter shapes had sizes similar to that of the parallelepiped. They were previously measured with a caliper and 3D digitized with photogrammetry in different overlap configurations with a camera-ground distance of 1.2m, forward overlap ranging from 75% to 95%, and lateral overlap from 67% to 90%. A parameter called "Power Of Unit" (POU), which considers simultaneously the image resolution and the longitudinal and lateral overlap was used to compare the results. Among different other considerations, it was shown that "the average measurement errors dropped dramatically with the increase of POU" (i.e., with larger overlaps).

In order to make the above-mentioned data comparable to each other and to the data reported in the experimental section of this research, the design factor was calculated and other opto-geometrical parameters for the different situations described in the articles referenced above are reported in Table 4.3.

Table 4.3. Design factor q calculated for the different papers mentioned in this section with the overlap, sensor size and focal length provided by the authors in the respective papers.

Paper	Sensor size (mm x mm)	Focal length (mm)	Distance (m)	Baseline (m)	Overlap	q
Haala & Rothermel, 2012	6.16 x 4.62	5.9	115	30	75%	3.84
Dandois et al., 2015	6,16 x 4,62	4.0	80	4.9	96%	16.3
				9.8	92%	8.2
				14.7	88%	5.4
				19.6	84%	4.1
				24.5	80%	3.3
				29.4	76%	2.7
				34.3	72%	2.3
				39.2	68%	2.0
				44.1	64%	1.8
				49.1	60%	1.6
Ni et al., 2018	23.4 x 15.6	16	300	29.1	90%	10.3
				58.3	80%	7.5
				87.4	70%	3.3
				116.6	60%	0.8
Zhou et al., 2018[24]	6,16 x 4,62	4.0	1,2	0.069	95%	17.3
				0.208	85%	8.9
				0.346	75%	4.0

Although several quantitative analyses have been conducted in the field of aerial photogrammetry to establish how the SfM/IM approach influences the optimal distance/baseline ratio, no similar study has been done for close-range data sets with convergent lines of sight. In particular, the various pas experiences in 3D digitization of CH based on SfM/IM photogrammetry [Guidi et al. 2018; Guidi et al. 2015b], and a preliminary study based on qualitative evidence emerging from such experiences [Guidi et al. 2015a], made evident a lack of scientific information about a possible optimal level of the *q* ratio in such applications. The purpose of this part of the research is, therefore, to fill this gap by exploring with high granularity how the 3D measurement uncertainty changes in correspondence with different *q*, considering a small camera-target distance survey, similar to what happens in surveying stone sculptures or other museum artifacts.

4.2.2 Materials and methods

This part of the research defines a methodology to explore the influence of image lateral displacement by comparing the photogrammetric models of specific test objects with the accurate models produced by a metrology grade 3D device based on pattern projection. The test objects were five stones with different geometrical structures and surface properties. These stones were first digitized by using a very accurate and precise pattern projection device, with

[24] For coherency with the other works, only the forward overlap has been reported here, although this part of the research also discusses the lateral overlap and their combined effect on the photogrammetric results.

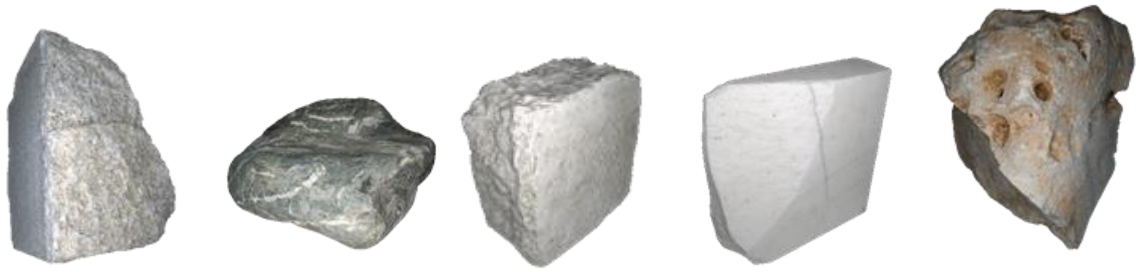
measurement uncertainty below 20 micrometers, to create the reference models. The same objects were then photographed under controlled conditions giving a fixed and small angular rotation to the object with respect to the camera in consecutive images. Each image set gathered with the minimal angular displacement (i.e., made of the maximum number of images) was then aligned using the SfM process, obtaining in this way also a robust estimation of interior and exterior camera orientations. On the aligned images several image matching processes were run, each time skipping one image every two, three, and so forth up to seven images in every eight, in order to implement different distance/baseline ratio conditions. The resulting dense clouds were then accurately aligned and scaled against the reference model in order to reduce the possible systematic error to a negligible component. The final step was to estimate the standard deviation of error of each cloud versus the corresponding reference model for the purpose of estimating possible trends in 3D quality vs. angular rotation, the latter being directly related to the distance/baseline ratio.

Test objects

Five stones of different shapes and surface properties were carefully selected. This selection was made to simulate the surface properties of different materials that are mostly used for the making sculptures, ranging from more to less optically cooperative surfaces.

The first stone was an irregular piece of granite with a sharp cut on one side. Its shape is therefore a combination of a flat planar surface with sharp edges on one side and irregular shapes on the other side. Its texture has a blend of dark spots on the light background, which favors the feature's detection process. (Figure 4.10a).

The second stone (Figure 4.10b) was a sedimentary rock smoothed by the water of a river. For this reason, it has a continuous smooth surface with round edges. The texture was a mix of prevailing uniform dark brown with whiteish veins that could be suitable for automatic feature extraction.



(a) (b) (c) (d) (e)

Figure 4.10. The five stone samples used as test objects in the experiments: (a) Granite; (b) Sedimentary rock; (c) Limestone; (d) Marble; (e) Sandstone.

The third sample (Figure 4.10c) was a roughly cuboid piece of limestone with irregular surfaces, an opaque appearance, and a light speckled texture that makes it very suitable for SfM photogrammetry.

The fourth specimen was a regular box-shaped slab of marble with a large chip of material lacking on a side (figure 1d). The shape is therefore mostly regular apart from the broken part that presents an irregular surface. The material, in this case, is optically non-cooperative, as demonstrated by tests with active 3D devices [Godin et al. 2001; Guidi et al. 2009b], due to its sponge-like microstructure that causes light to be reflected not only by the exterior surface but also by several inner layers of material.

The fifth sample was a piece of sandstone with the most irregular shape among all the objects of the set, including nearly flat surfaces, sharp-edged, rounded zones, and several surface cavities (Figure 4.10e). The feature detection process is highly affected in the parts where the cavities are present. Except for these cavities, the shape and surface colors elsewhere on this object are suitable for enough feature detection during the photogrammetric process.

Devices

To create accurate reference models, a precision range sensing device was used. The eviXscan 3D Optima Heavy Duty is a blue light pattern projection device, from Evatronix S.A. equipped with one central blue light stripe projector and two lateral 5 Mpixel cameras (Figure 4.11a). With one shot it generates a 5 Mpoint range map reducing the effect of possible occlusions thanks to the double camera. It achieves a high density of 3D point clouds (up to 116 pt/mm2), corresponding to a lateral resolution better than 0.1 mm. The wavelength of blue light helps to limit the influence of ambient light on the measured data (Figure 4.11b). Furthermore, owing to the low diffraction of blue light, the resulting measurements are more accurate than those originating from the white-light patterns. The measurement accuracy provided by the manufacturer is up to 18 µm, evaluated in the factory through the procedure defined by the German metrological standard VDI/VDE2634, part 2. The measurement volume is 250 mm x 170 mm x 120 mm.

(a) (b)

Figure 4.11. 3D digitizer used for creating the high accuracy and high-resolution ground truth 3D model for evaluating the dense point clouds created by photogrammetry: (a) eviXscan 3D Heavy Duty Optima pattern projection device with one central projector and two 5Mpixel cameras on the sides; (b) test object placed on the turntable attached with the device while illuminated by one of the blue light stripe patterns.

The device was mounted on a tripod and connected with a turntable which can be controlled by entering a turning angle for each measurement into the device's control software (eviXscan 3D Suite). In this way, all the range maps generated for an entire 360-degree turn can be pre-aligned automatically. The final alignment is then refined using an Iterative Closed Point (ICP) algorithm implemented in the eviXscan 3D Suite, which makes it possible to estimate the standard deviation of an error on the overlapping areas of the various range maps.

The photographic equipment for this test was selected based on previous experiences with the photogrammetric survey in the most difficult situations for photogrammetry. The combination of camera and lens is the one that has been used for digitizing the archeological sculptures placed near to walls, under the auspices of the IU-Uffizi project. As learned from the photogrammetric survey during this massive 3D digitization of the sculptures, the placement of several sculptures in the museums does not support photography from sufficiently long distances. For such situations, a wide-angle lens is required to shoot images from short distances. Furthermore, there are several locations inside the museums where enough natural light is not present, especially inside the exhibition rooms. In these cases, to photograph the dark areas of sculptures, an artificial ring light has been used in the project. The combination of the camera sensor, lens, and ring light allows for taking suitable images for photogrammetry for a sensor-to-object distance as small as 20cm, even in the absence of natural light.

To simulate the actual difficult situations of the photogrammetric survey in the field, but also for creating a controlled and repeatable lighting condition for all the different experiments, the same combination of the camera (Figure 4.12a) and lens (Figure 4.12b) coupled with the ring illuminator (Figure 4.2a) was used for the tests presented in this section.

To avoid any possible oscillation during the shoot, the camera was equipped with the “Smart Remote Control” function, which makes it possible to connect the device to a tablet or a smartphone using the app “Sony Play Memories.“ Through the wi-fi connection, the viewfinder and the controls over shutter speed, aperture, and ISO sensitivity are remotely available on the connected portable device. The focus can also be remotely set on a specific point by tapping on the desired area over the remote viewfinder.

(a) (b)

Figure 4.12. The photographic equipment used in the tests: (a) Sony a6000 camera body with CMOS sensor featuring 24 MPixels; (b) Zeiss Touit 12 mm f/2.8 lens.

4.2.3 Reference 3D models

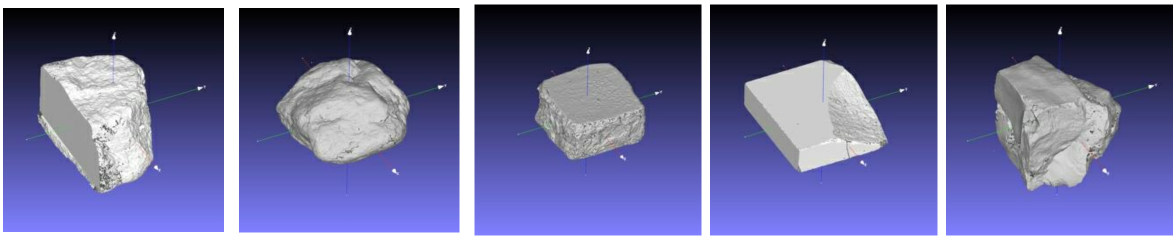
To create the accurate reference models to be compared with the point cloud generated by photogrammetry, the pattern projection device described in the previous section was used. Several range maps were captured by the eviXscan 3D Suite. Thanks to the turntable controlled by the software, the range maps were automatically pre-aligned for a complete rotation of the test objects from different points of view.

These stripes of aligned 3D images were then manually pre-aligned each to the others, and all the range maps covering the complete surface of the test objects were then globally registered through the ICP algorithm embedded in the software. The residual RMS error among different aligned range maps was evaluated over the overlap areas, providing values ranging from 10 to 20 µm, coherent with the accuracy declared by the manufacturer. Such error represents at least one-fifth of the uncertainty of the photogrammetric point cloud, being generally above 100 µm under the chosen capturing conditions.

Finally, the aligned range maps were merged in the form of a mesh applying the 3D data interpolation algorithm implemented by the Evixscan 3D. Here all the points of the 3D cloud are also nodes of the mesh. In this way no smoothing of the acquired data occurs, maintaining, therefore, the accuracy of the raw 3D data. Because of the high density of the device's measurement points, the resulting mesh had a large number of faces (on the order of tens of millions) to be used as a reference for comparison with the point clouds from photogrammetry with many fewer points (in the order of 2-3 million).

Therefore, both the metrological properties of the scanned data and their spatial density were suitable for being used as a reference for comparison with the photogrammetric 3D clouds.

The meshes for all the test objects were exported in STL format. Before doing the comparison, all the meshes were topologically cleaned and oriented in Meshlab, the well-known open-source mesh processing software developed by the Visual Computing Lab at ISTI-CNR, Italy [Cignoni et al. 2008]. The cleaning process was performed to remove duplicate vertices and faces, non-manifold edges and vertices, and zero area face, in order to remove any possible systematic uncertainty in the comparison.



(a) (b) (c) (d) (e)

Figure 4.13. Meshes of the test objects were created by active 3D digitization with the pattern projection range device. Each 3D model was translated with the origin of the reference system on its barycenter with xy representing the horizontal plane.

The orientation was a translation of the coordinate system to the barycenter of each mesh and a rotation for having an ordered representation of the 3D models, as shown in Figure 4.13. Such meshes allowed a precise measurement of the bounding box of each reference sample, as reported in Table 4.4. The numbers make evident that all the objects fall within the same order of magnitude with a diagonal roughly ranging from 300 to 400mm. This feature makes them suitable for a comparison where the 3D capturing method remains the same (SfM photogrammetry), the opto-geometrical conditions are controlled, while material and texture change from case to case.

Table 4.4. Bounding box sides and diagonals of each reference 3D mesh.

Sample	x (mm)	y (mm)	z (mm)	d (mm)
a	277.1	209.6	182.6	392.5
b	280.2	250.7	175.3	414.8
c	194.8	217.5	91.8	306.1
d	253.1	225.0	66.4	345.1
e	256.5	230.0	211.3	404.2

4.2.4 Methodology for generating the photogrammetric dense cloud

Experimental set-up

The rig for performing the photogrammetric survey was designed in a simple but effective way. It was composed of three components (Figure 5): (i) a manually rotating platform at the center of which the test object was placed and that allowed a minimum angular rotation of π/60; (ii) the first tripod with an arrowhead mounted on the top to point at the angular scale for controlling the rotation; (iii) a second tripod holding the camera equipped with the 12mm lens and ring illuminator described in the previous section.

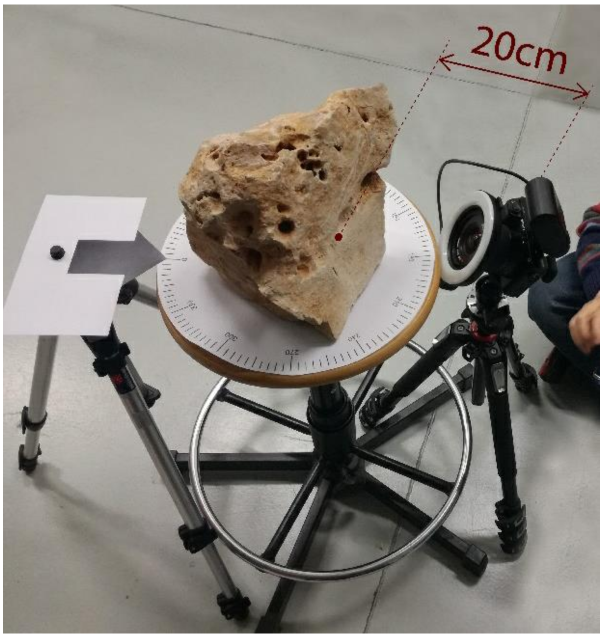


Figure 4.14. Experimental set-up for generating images sets at controlled angular steps, involving a small, fixed lateral displacement.

The distance between the nearest point of focus on the object and the sensor of camera was kept at 200 mm, as allowed by the combination of camera, lens, and ring illuminator described in the previous section. By using this setting, it was possible to photograph the test objects with a minimal lateral displacement given by the distance between the sensor and the center of rotation, multiplied by the angular step $\Delta\theta=\pi/60$.

Considering the size of each object roughly represented by the diagonal of each bounding box reported in Table 4.4, the distance between the camera and the rotation center can be approximately estimated as:

$$\boldsymbol{h = \frac{d}{2} + 200\,mm} \tag{3}$$

The minimal distance between adjacent shots (i.e., the minimal baseline of the photogrammetric image set), was, therefore:

$$\boldsymbol{b = h\frac{\pi}{60}} \tag{4}$$

So, by evaluating the camera-target distance fixed at 200 mm, the maximum q factor considered in these experiments can be calculated as a function of the object size d:

$$\boldsymbol{q = \frac{60}{\pi\left(\frac{d}{400} + 1\right)}} \tag{5}$$

The following photogrammetric process will consider different image subsets of the denser one by skipping n-1 images every n, with n ranging from 1 to 8. This will involve an angular displacement Δθ=nπ/60, and consequently, b(n) will be:

$$\boldsymbol{b\,(n) = h\frac{n\pi}{60}} \tag{6}$$

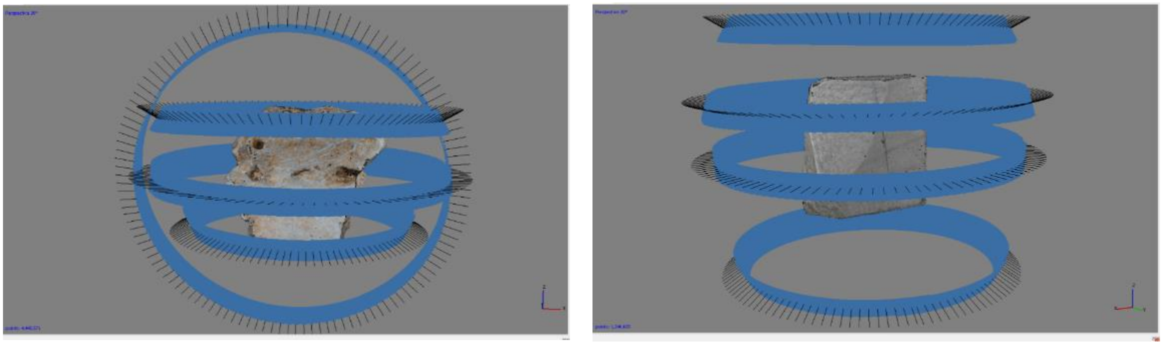
Consequently, the q factor in correspondence of different skip levels n will be:

$$\boldsymbol{q(n) = \frac{60}{n\pi\left(\frac{d}{400} + 1\right)}} \tag{7}$$

Image capturing protocols

In all the shooting sessions the images were saved using the Sony RAW image format (ARW). This made it possible to maintain the whole 12-bit dynamic range captured by the camera sensor, allowing a possible image balancing in a subsequent phase in case of non-uniform light distribution throughout the photogram. However, since the capturing was made under very controlled conditions, such post-processing turned out to be unnecessary, and the images were directly converted into jpeg (8-bit) for the following photogrammetric processing. The conversion was carried out with the commercial software package Lightroom (Adobe) at the lowest compression level.

For each object, four blocks of 120 images were taken all around the test object to cover the entire 2π rotation. As shown in figure 6, two different camera distributions around the object were used.



(a) (b)

Figure 4.15. The protocol for capturing photos of the test objects: (a) used for test objects "a" and "e"; (b) used for test objects "b", "c" and "d".

The first configuration (Figure 4.15a) was composed of three horizontal image blocks taken with the point of view at three different heights and the camera aiming at the center of the object. To connect the first three blocks, a block of images whose projection centers are on a plane orthogonal to the planes defined by the projection centers of the other three blocks was used. In all of these blocks, the minimum distance of 20cm between the point of focus on the object and the camera sensor was maintained. Based on the literature and the lessons learned from past experiences, such a protocol for image capture has proven to produce the best results from photogrammetry.

Nevertheless, in actual conditions, this capturing geometry is not always able to maintain a stable positioning of the sample over the rotating stand. In such cases another configuration was employed, where all the images are captured in blocks at different heights with higher overlap among the different blocks but without any dataset defining a plane orthogonal to the other three (Figure 4.15b).

Although the former would be theoretically preferable, the latter also represents a reliable shooting protocol, extensively tested in digitizing museum objects located in contexts where moving all around the object is not possible.

Image processing and photogrammetry

Although several commercial and open source solutions are now available for implementing the SfM/IM pipeline, in this study Agisoft Metashape Pro (St. Petersburg, Russia) was used. This software package has been used widely in museum and archaeological applications and has been widely reported in the literature. The software package (v. 1.5.5) was run on a Windows desktop PC configured with an Intel i7-6800k CPU (8 cores), 64GB RAM, 512 GB SSD hard drive, equipped with an NVIDIA GeForce 1080 GPU with 4GB RAM.

The photoshoot of each object produced four 120 image blocks for a total of 480 images per object. Even if there was a black background, all the images were manually masked before the feature extraction step to prevent possible steady features in the scenes from interfering with the SfM process. In this way, only the features extracted over the stone surface were used as tie points for calculating the mutual orientation of the images and the camera calibration parameters.

For each test object the related 480 masked images were aligned and used as starting point for the point cloud generation. The Metashape Pro software supports setting up several parameters for aligning the images. In all the experiments the aligning accuracy was set at "High" to perform the feature detection process on the original photos without downscaling them. The key point limit represents the upper limit of detected features to be taken into account during the alignment process. The tie point limit represents the upper limit of matching features for every image. Setting too high or too low a value for both these numbers might result in a big number or in less reliable features. Therefore, the key points and tie points limits were set to 40,000 and 10,000 respectively and the feature detection process was constrained by the previously created masks.

The IM phase for generating the dense clouds was repeated several times starting from the same alignment by using all images at the first step and gradually skipping images for subsequent IMs: one is taken and one skipped in the second run, one taken and two skipped in the third, and so forth until seven images were skipped after every aligned image in the last dense cloud generation. As the minimum angular displacement between consecutive images was set to be $\pi/60$, the resulting eight IMs included images with an angular displacement of $\Delta\theta=n\pi/60$, where n is the "skipping level" ranging from 1 to 8. In this phase one of the main adjustable parameters is the "Quality," which defines the size of the matching patch in the IM process. It can range from 1x1 pixel (ultra-high) to 16x16 pixels (lowest). Apart from the misleading choice of nomenclature for this parameter that essentially defines the density of the 3D dense cloud rather than its quality (which tends to be better for larger matched patches), our choice was to use the 4x4 matching patch, labeled by the software as "Medium." That is the default value proposed by the procedure and based on previous experiences it gives the best tradeoff between cloud density, 3D uncertainty, and processing time. The other parameter that was optimized for this process is the "Depth Filtering," which was chosen to be "Aggressive" in order to sort out most of the outliers.

No scaling based on GCPs or reference distances was performed at this stage. The resulting dense clouds were exported in the form of a text file with six columns representing the location (xyz), color (RGB), and normals (NxNyNz) of each acquired point.

4.2.5 Photogrammetric data scaling and comparison with the reference mesh

These two last steps of the process involved the use of the software CloudCompare.

As the point clouds resulting from the process described above are not scaled, before starting the comparison all point clouds were roughly scaled based on approximated measurements taken on the mesh model created by the pattern projection device. These coarsely scaled models were then manually aligned with the reference mesh. Afterward, the ICP algorithm embedded in CloudCompare was run twice for 50,000 points, first by only roto-translating the point cloud to the reference and a second time for finely adjusting the scale and orientation of the point cloud with respect to the reference mesh.

The residual deviation of the 3D coordinates gathered with photogrammetry from the reference mesh was then statistically analyzed to calculate RMS error, mean error, and error histogram. It was made sure that the scaling/orientation step was iterated until the mean value was less than 10 µm for each dense cloud. The purpose was to confirm that the alignment and scaling process were performed correctly, not influencing in this way the random error estimation with a systematic component.

This process was repeated for all 8 point clouds of each one of the 5 test objects, for a total of 40 measurements of point-cloud vs. reference mesh. The results of such comparisons are reported in the next section.

4.2.6 Findings

After the photoshoot, five sets of 480 extremely overlapped jpeg images were aligned in around 2 and one-half hours on the workstation mentioned above. All the images were properly aligned for each of the five test objects.

The alignment process yielded more than 200k tie points in all cases. The protocol used involved the elimination of possible tie points with a reprojection error above 0.45 pixels and the optimization of the camera parameters with the remaining high-quality tie point. In this way, the reprojection error of tie points was better than 0.5 pixels for all five of the test objects.

The following dense cloud generation proceeded as described in the previous section. Eight subsets of the 480 aligned images were processed, selecting all the images, skipping one image every two, two every three, and so on, up to one image taken and seven skipped. The consequent angular displacement between adjacent images was $\Delta\theta = n\pi/60$; n=1,2, ...8. The corresponding image sets were therefore made by a decreasing number of images, ranging from 480 for the first set to 480/8=60 for the last one, as reported in detail in Table 4.5.

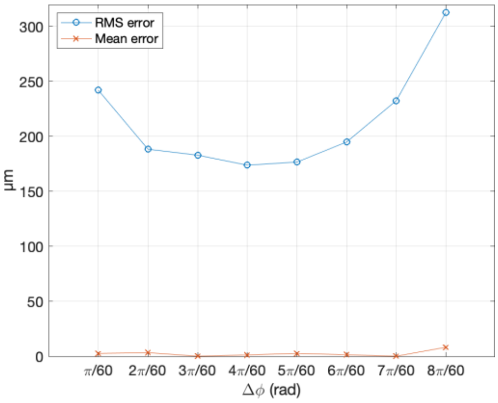
Table 4.5. Image sets processed for each object.

Set	Δθ	#images
1	π/60	480
2	2π/60	240
3	3π/60	160
4	4π/60	120
5	5π/60	96
6	6π/60	80
7	7π/60	68
8	8π/60	60

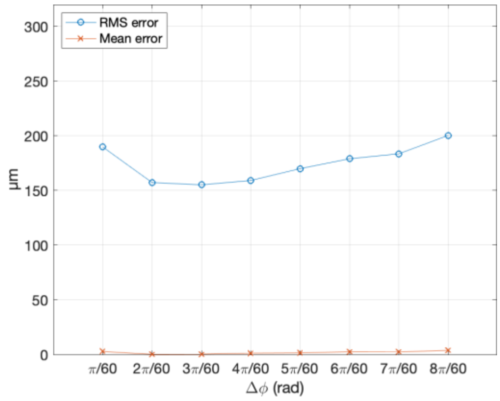
Table 4.6. RMS error resulting from the comparison between the various point clouds originated by different angular displacements and the mesh reference, for the five test objects.

Δθ (rad)	Sample a (μm)	Sample b (μm)	Sample c (μm)	Sample d (μm)	Sample e (μm)
π/60	242	190	207	241	136
2π/60	190	157	168	212	127
3π/60	181	155	163	183	126
4π/60	174	159	164	200	129
5π/60	188	170	172	214	134
6π/60	195	179	186	237	146
7π/60	201	184	244	251	150
8π/60	241	200	304	271	173

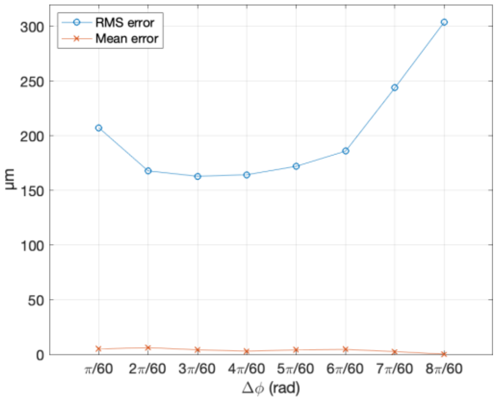
Given the size of the objects and the related image distribution in space, these settings provided more than 2 million points for each of the 40 dense clouds created in this way (8 IMs at different lateral displacements replicated on all the 5 objects). The comparison of such 3D point clouds against the reference mesh, evaluated on all the test objects, gave the values reported in Table 4.6.



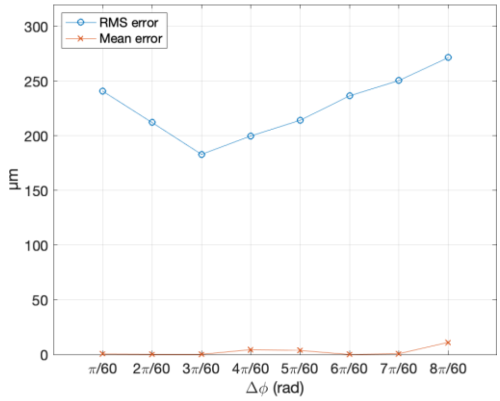
(a)



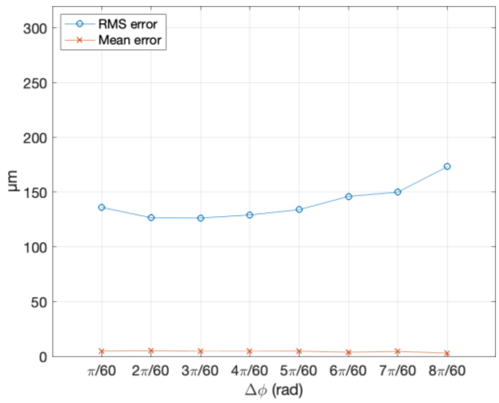
(b)



(c)



(d)



(e)

Figure 4.16. RMS error and Mean error obtained by comparing eight different dense clouds created by various angular displacements with the reference mesh: (a) Granite sample; (b) Sedimentary rock sample; (c) Limestone sample; (d) Marble sample; (e) Sandstone sample.

For the sake of clarity these values, representing the standard deviation of error of the 3D points created by the photogrammetric process with respect to the reference mesh, have been plotted in Figure 4.16. The figure shows the behavior of the RMS and the corresponding Mean error in correspondence of different angular displacements between one image and the adjacent one for all the five samples chosen for the experiment.

In order to make them comparable with the data reported in the literature, these results needed to be plotted against the distance/baseline ratio *q* that has been used as the common reference for analyzing the conclusions reached in the other papers. The quality factor q corresponding to the different angular displacements can be calculated with Eq. (7), by approximating the size of each object with the diagonal of the related bounding box reported in Table 2. The q calculated for all the 40 combinations of object size and angular displacement are reported in Table 4.7.

Table 4.7. Quality factor q calculated in correspondence to different angular displacements (column 1) and the different object sizes (in parentheses below each sample identifier).

Δθ (rad)	Sample a (393 mm)	Sample b (415 mm)	Sample c (306 mm)	Sample d (345 mm)	Sample e (404 mm)
π/60	9,64	9,38	10,82	10,25	9,50
2π/60	9,32	9,33	9,30	9,31	9,33
3π/60	6,22	6,22	6,22	6,22	6,22
4π/60	4,70	4,70	4,70	4,70	4,70
5π/60	3,78	3,78	3,78	3,78	3,78
6π/60	3,15	3,15	3,15	3,15	3,15
7π/60	2,71	2,71	2,71	2,71	2,71
8π/60	2,37	2,37	2,37	2,37	2,37

Owing to the similarity in size of different samples, the related values are nearly identical except for the smaller baseline (Δθ = π/60) where q ranges from 9.38 associated with the larger object (sample 2) to 10.82 for the smaller one (sample 3). In this case, the average value across samples is 9.92. Such values allow us to plot the RMS error behaviors, shown in figure 7 in correspondence of Δθ, against the quality factor q (figure 8).

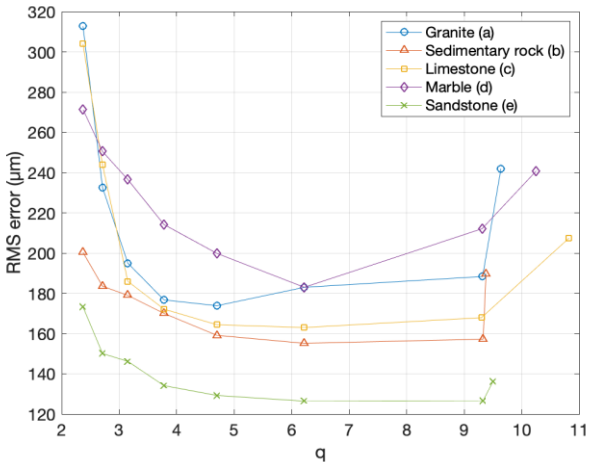


Figure 4.17. RMS errors of table 4 represented against the values of q shown in table 5 for the different samples.

Although the behaviors illustrated in both Figures 7 and 8 made it possible to identify a consistent lowering of the RMS error from the second angular step with regrowth of the curves after the 4th step, a comparison among the different cases is not easy. This arises from the rather different absolute values of the errors determined by the different shape, texture, and material-light interactions of the various samples. Therefore, all sequences referring to the minimum RMS error associated with the 8 sequences originated by each object were, normalized, obtaining the values reported in Table 4.8.

Table 4.8. Normalized RMS error with respect to the minimal value in the sequence associated with each object. The yellow values represent image configurations giving a normalized error lower than 1.1 (i.e., RMS error within 10% of its minimal value in the sequence).

Δθ (rad)	q	Sample a	Sample b	Sample c	Sample d	Sample e
π/60	9,9[25]	1,392	1,223	1,272	1,315	1,077
2π/60	9,3	1,095	1,013	1,030	1,159	1,002
3π/60	6,2	1,042	1,000	1,000	1,000	1,000
4π/60	4,7	1,000	1,025	1,009	1,092	1,022
5π/60	3,8	1,081	1,096	1,056	1,170	1,061
6π/60	3,2	1,122	1,153	1,141	1,292	1,156
7π/60	2,7	1,154	1,183	1,496	1,369	1,187
8π/60	2,4	1,386	1,291	1,865	1,483	1,371

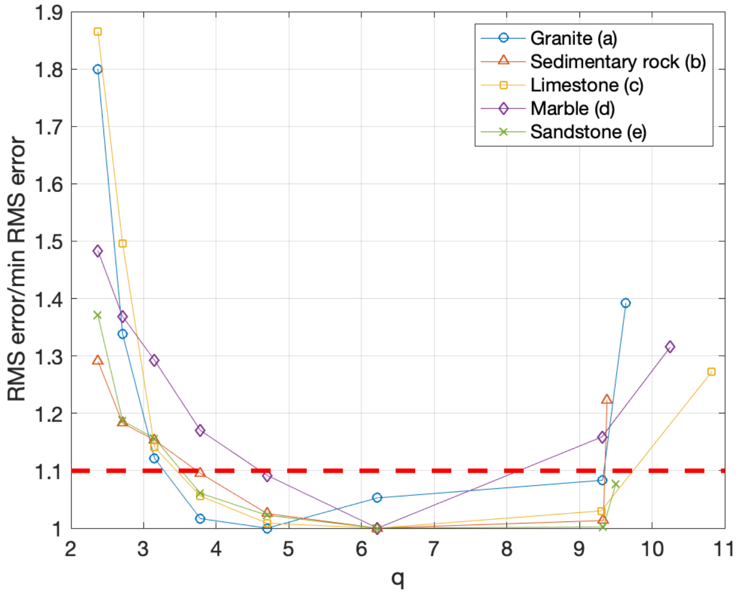


Figure 4.18. Normalized RMS errors for the different samples and different lateral displacements, also shown numerically in Table 6, plotted as a function of q.

[25] This value represents the average of the various values of q for the different samples at Δθ=π/60 (first row of Table 5). The following q values are instead the same for all objects if considered at the first decimal digit and did not require any averaging.

From this rearrangement of the RMS error, also shown in graphical form in Figure 4.18, it is possible to see the behavior more clearly. Each trend starts with a non-minimal value at the minimal lateral displacement among photograms (the rightmost samples in the diagram of Fig. 9), has a minimum after two or three angular steps (central area of the diagram), and tends to regrow for higher values of the angular step, namely for lower values of q (leftmost side of the diagram).

This behavior appears to be consistent for all the analyzed specimens, independently of size, texture, and material properties, with just minor behavioral differences depending on the specific sample.

In particular, “Sample a” presents a minimal RMS error (normalized value = 1) for q=4.7, while all the other samples have the minimal for q=6.2.

With the plot of Figure 4.18, we can also see for which q values the error remains below a predefined threshold represented by the dashed line, arbitrarily fixed at 10% above the minimal RMS error. The diagram indicates that most of the values below the threshold correspond to the central part of the diagram.

To give a more quantitative representation of this evidence resulting from the data, the “low error” situations are also represented with a yellow background in Table 4.8, represented by values of the RMS error below the threshold. We can see that the errors within 10% of the minimum (i.e., normalized values < 1.1) tend to describe a pattern covering the first 5 lines of the table, corresponding approximately to values of q ranging from 9.9 to 3.8.

This result has been quantified in Figure 4.19 by representing the number of occurrences of the “low error” condition across the different test objects.

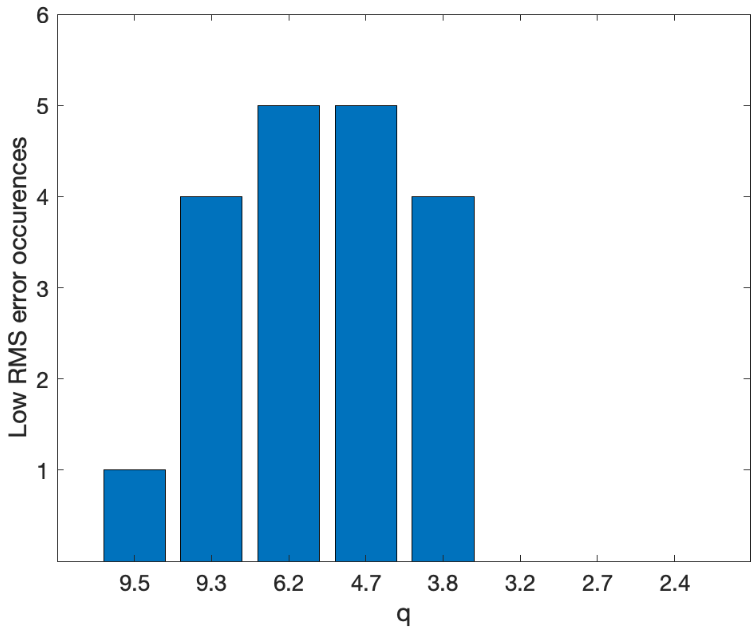


Figure 4.19. Histogram of occurrences where the RMS error is within a 10% tolerance from the minimum across the different test objects used in the experiments. We can see that the large majority of “low RMS error” conditions corresponds to q=[3.8-9.3], while the range q=[4.7-6.8] identify the range where the point clouds of all the five objects exhibit such low RMS error.

To make this research comparable with textbooks and previous studies in the literature, the parameter through which the different cases were compared was q, the ratio between the average camera-target distance of two adjacent shots, and their mutual distance (baseline). This parameter has been mentioned directly by some sources as crucial in determining the quality of the 3D outcome of a photogrammetric measurement [Luhmann et al. 2014; Waldhäusl and Ogleby 1994; Waldhäusl et al. 2013]. It was also calculated for some data contained in published articles dealing with the influence of image overlap on the quality of aerial photogrammetry [Haala and Rothermel 2012; Dandois et al. 2015; Ni et al. 2018; Zhou et al. 2018], in order to establish a common basis for the comparison.

Given the potential unmanageable number of experiments for analyzing any possible situation, the study has been focused on a volume size typical of museum artifacts, using a photographic configuration broadly and successfully employed in several activities of massive 3D digitization of cultural heritage using SfM/IM photogrammetry.

The study was carried out by analyzing several dense clouds obtained by different spatial distributions of cameras providing a considerable span of q [2.4 – 9.5]. The dense clouds were created by imaging five stone specimens previously characterized with a high accuracy 3D active device and denoted as "a," "b," "c," "d," and "e."

The experiments reported show that differently from what has generally been claimed for traditional photogrammetry, wherein convergent shooting for close-range photogrammetry the optimal q lies in the range [0.4–0.8] [Luhmann et al. 2014], in close-range photogrammetry based on SfM/IM such value grows significantly. In the experimental conditions described in this section, the results show a lower RMS error at q= 4.7 for sample a, and at q=6.2 for all the other samples (b to e). The histogram represented in figure 10 also shows that if we indicate an increase of the RMS error within 10% of its minimum as a "low error" condition, the photogrammetric dense clouds generated by all the five samples, satisfy the "low error" condition for q in the range [4.7 - 6.2], one order of magnitude larger than the values supposed to be optimal in traditional photogrammetry.

Even if in principle the results shown here should be valid independently of the volume considered, this specific result gives useful support for defining a convergent cameras geometry for photogrammetric surveys of volumes in the order of a museum object, when the key feature to be pursued is the lowest measurement uncertainty (i.e., the best 3D quality).

5. EVALUATION OF CULTURAL EXPERIENCE WITH 3D TECHNOLOGIES: MIXED METHODS RESEARCH

3D dissemination of CH objects through technologies such as augmented reality, virtual reality, and 3D printing has impacted the fields of art history and cultural heritage and has become more common. Yet, studies that go beyond the technical aspects of 3D technology and treat such topics for their significance for restoration, conservation, engagement, education, research, and ethics hardly exist. The aim of this section of the research is twofold: on the one hand, it aims to get a better understanding of the applicability of each technology for different purposes (education, research, conservation/restoration, and museum presentation), and, on the other hand, it focuses on the perception of these technologies.

The chapter has been divided into three sections with each section providing details about protocols and procedures adopted for the data collection and evaluation activities from the stakeholders of this research:

- interviewing the researchers/ scholars in related fields in the United Kingdom (UK)
- a collaborative workshop in the Netherlands involving all the stakeholders of this research (Researchers/ scholars, art historians/ archeologists / Museum professionals, designers, engineers/ digital application developers, and museum visitors)
- interviewing and evaluation of the interaction of the visitors of a digital application in the ambient of a museum exhibition in Italy

5.1 Interviews with the scholars in related fields

The practical part of qualitative data collection started by interviewing prominent scholars in the fields related to this research. Even though useful insights from the past research were collected during the literature review, interviewing the scholars was important to validate the lessons learned from their research and the projects in which they participated.[26]

[26] Interviewees:

- Areti Damala - Department of Computer and Information Sciences - University of Strathclyde. Her research focuses on understanding how interactive technologies can assist us in shaping both affective and effective museum visiting experiences.
- Areti Galani - School of Arts and Cultures - Newcastle University. Researcher in the design, study and understanding of digital applications in cultural heritage for the purpose of interpretation, learning, and exhibition design.
- Daniela Petrelli - School of Interaction design - Sheffield Hallam University. Her research focuses on novel forms of interaction design that combine digital technology with product design, also known as Tangible and Embedded Interaction.
- Luigina Ciolfi - School of Interaction design - Sheffield Hallam University. She is a human-computer interaction and Computer-Supported Cooperative Work researcher.
- Marco Mason - School of Design – Northumbria University. His research is at the intersection of Digital Cultural Heritage, Design, and Organizational studies for theorizing the development and implementation of digital technology in the museums and culture sector.
- Paola Di Giuseppantonio Di Franco - School of Philosophy and Art History - University of Essex. Her research combines material culture, heritage, and cognitive science to explore how new technologies impact heritage making processes and the interpretation processes of the past.

This activity was carried out under the scope of the Erasmus plus traineeship program at the school of Design of Northumbria University in Newcastle, United Kingdom. During this period, a protocol for conducting semi-structured interviews was developed and several scholars in the fields related to this research in the UK were interviewed:

- Digital Heritage
- Museum Studies
- Design for Cultural Heritage
- Interaction Design for Cultural Heritage
- Art History and Digital Archeology

The semi-structured interviews were designed based on the methods described in the literature [Kvale 2008; Galletta 2013]. This method is effective for qualitative research, as it is sufficiently structured to focus on the topic, while at the same time it leaves space for a conversation and to add narratives of the participants. The interviews were designed with three segments: i) the opening segment with open-ended questions; ii) the middle segment with more specific questions and iii) a concluding Segment to revisit the narrative of the participant and their suggestions. As the discussions were recorded for later analysis, after each interview, the interviewees were asked to sign a form of consent.

Due to the fact that the interviews were semi-structured, the conversations took different paths in each of the interviews, but the overall focus of these interviews was as follows:

- discussing the effectiveness of models and frameworks and the differences between them for designing projects for museums with technology
- how to implement digital technologies in the CH sector
- The role of 3D digitization in education, museum presentation research, and preservation of CH
- Analyzing the projects in which the participants have been involved in the past. The analysis was made on the design of experience by the use of digital media and the overall effectiveness of the projects

The transcriptions of interviews were analyzed by using content analysis [Mayring 2015]. It was used to develop the methodology for this research (chapter 1), to better understand the functionality of models and frameworks, and to fathom the impact of digital technologies in the CH sector. The analyses of these interviews, combined with the other qualitative and quantitative data collected throughout this research, were also used as the starting point for creating a framework of cultural experience (chapter 6).

5.2 Significance of 3D Reproductions of Cultural Heritage: A collaborative workshop involving stakeholders of research

As the world's art and CH objects become digitized and widely available to us thanks to digital technologies, we have started to look at artworks differently as they have become accessible beyond the physical confines of a museum's walls. Technology reshapes the engagement with and the perception of these objects as it provides possibilities and new opportunities hitherto unimaginable. This inevitably affects our perception of art and cultural heritage artifacts. The perception of art here is referred to the complex multifaceted relationship between the work of art as a visual starting point and the viewer's personal understanding of and emotional connection to it. Furthermore, these potential shifts in the perception of art will evidently have effects on how the viewer understands the authenticity, originality, and genuineness of an artwork.

Authenticity, on the other hand, is a complex term capable of being interpreted in several ways depending on such factors as a person's (cultural) background, religion, ethnicity, gender, and age. From the Western perspective from which this research has been conducted, the authenticity of an artwork is oftentimes sought in its tradition of creation and is proved by its use of genuine materials. Needless to say, 3D reproductions fall outside what can be considered authentic in this sense [Khunti 2018]. Yet, if we consider the fact that art's value does not solely rely on its static materials but also on its contextual and conceptual meaning, we may rightly insist that authenticity arises from both an object's material qualities and also its more conceptual and intangible interpretative perspectives. With this background in mind, we are in a position to understand the impact of these technologies on our perception of art and to grasp the significance and applicability of these technologies in museums and other CH fields.

This section of the research aims to provide a better understanding of the perception of various methods of digital and physical 3D reproduction (AR, VR, digital screen displays, 3D printing) and to evaluate their applicability. Furthermore, it sheds light on the consequences of the introduction of these reproduction methods in the field of art and CH by analyzing the impact of these technologies on our perception of art. Although this study focuses on museums, the results could be considered helpful for the CH field more generally. It offers an exploratory investigation with an interdisciplinary approach focusing on analyzing the perception of reproductions among different stakeholders (designers, art historians, museum visitors, engineers) and for various purposes (education, research, conservation/restoration, and museum presentation). Furthermore, it uniquely tries to bring together the reflections of various stakeholders in a single study. On the basis of the analyses of data collected from the stakeholders (both professionals directly working with CH objects as well as non-specialists indirectly engaging with art), this study proposes ways in which 3D technologies can enhance cultural experiences in a way that respects the material and conceptual integrity of the original object and its creators.

The research questions that were addressed in this part of the research are:

1. How are the methods of 3D reproduction under study (AR, VR, digital screen displays, 3D printing) perceived on their own and in comparison to each other?
2. In what way can methods of 3D reproduction contribute to the experience of CH objects and artworks for museum education, CH research, conservation/restoration, and museum presentation?
3. What are the design factors to be considered in order to develop enhanced experiences and interactions with 3D digitized and printed CH objects in a museum setting?

To answer these research questions, existing data presented in the literature were combined with quantitative and qualitative analyses of data collected from stakeholders for creating evaluation criteria of experience with 3D reproductions. This research provides a contemporary evaluation of 3D reproductions. Museums can employ this evaluation to reconsider the use of 3D digitization and physical reproduction in fulfilling their mission and in creating new narratives in a world that imposes limits on the physical interactions permitted with works of art as well as museums themselves.

5.2.1 Case studies

In order to carry out this part of the research and promote discussions on the use of 3D reproductions for CH objects, case studies were used. The main case study - Laocoön and His Sons - was presented by means of various 3D reproduction methods. In addition to this case study, previous projects were also used: a video showing a 3D reconstruction of the Roman circus in Milan (CHT2 project), and a VR presentation of Leonardo da Vinci's Last Supper (LSI project). These examples helped by broadening the ways of presenting and interacting with the technologies under study. They also made it possible to include various types of CH artifacts, ranging from grand architectural scale models to sculptures and paintings.

Digital touch screen, AR, and 3D printing

The Roman statue Laocoön and His Sons (probably dating to the first century BCE and excavated in Rome in 1506) was selected as the central case study of this research. It was presented by means of various methods: an interactive digital touch screen, a mockup AR application created specifically for this research project, and a high-quality polychrome 3D print. The statue used in the case study is a copy of the original Roman statue (Vatican Museum in Rome - Figure 5.1b) made by the Florentine sculptor Baccio Bandinelli in 1520. It is currently on display at the Uffizi Gallery Museum in Florence (Figure 5.1a). A 3D digitized model of high-resolution geometry and texture was created through the auspices of the Indiana University-Uffizi 3D Digitization Project.

(a) (b)

Figure 5.1. Laocoön and His Sons: (a) by Baccio Bandinelli, 1520-1525, Marble, 208 cm × 163 cm × 112 cm, Uffizi, Florence; (b) by Hagesandros, Athanodoros, and Polydoros, 200 BC-70 AD, Marble, 208 cm × 163 cm × 112 cm, Vatican Museum, Vatican, Rome, Italy.

When showing the statue via a digital touchscreen, the high-resolution model was presented using Sketchfab – a web service for sharing and visualizing 3D models. The 3D model included the traditional information provided for a work of art (name, artist, date, material, dimensions, principal restorations, and bibliography) as well as the technical metadata about the author of the model and the way 3D data was captured. Furthermore, location-based annotations were added to the 3D model in order to clarify aspects of the statue and to be able to connect narratives belonging to the depicted story.[27] Owing to the high-resolution geometry and texture of the model integrated with the annotations, the user could navigate around the model, zoom in on details and explore both the formal and narrative information in a way that is not possible in a usual museum setting.

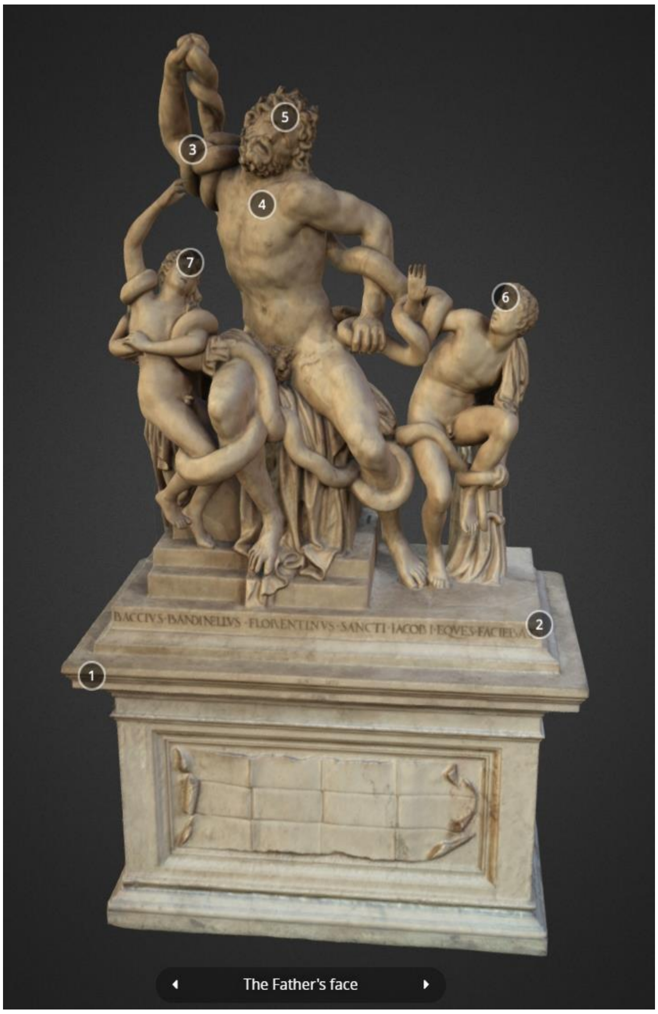


Figure 5.2. A high-resolution 3D model of an annotated model of Laocoön and His Sons on Sketchfab presented through a digital touch screen.

Furthermore, for this part of the research specifically, a mockup augmented reality application was created. The same 3D model of Laocoön and His Sons was used by integrating the model with

[27] https://sketchfab.com/3d-models/laocoon-and-his-sons-b6d161aa6d0e426dacc9899a7836e1c5

other 3D models, text/audio narratives, and educational animations. The application was created using the AR Creation Tools from Apple, which includes Reality Composer, Xcode, Reality Converter, and USDZ Tools.[28] Reality Composer is an application for iOS, iPadOS, and macOS to build and simulate AR experiences for iPhone or iPad. Xcode 11 and iOS13 are required to use the content created in Reality Composer.

The application could be navigated and used by superimposing the virtual model on any plane surface or a predefined anchor point. Once the model is projected within the physical environment, the user sees four different tabs for allowing the user to explore several facts and various assets of the statue:

- style of the sculpture
- dynamic effects present in the sculpture through the curvilinear movement of different elements that provides unity and movement
- comparison of different features of the sculpture with another sculpture stored elsewhere
- reconstruction of the colors in the digital environment

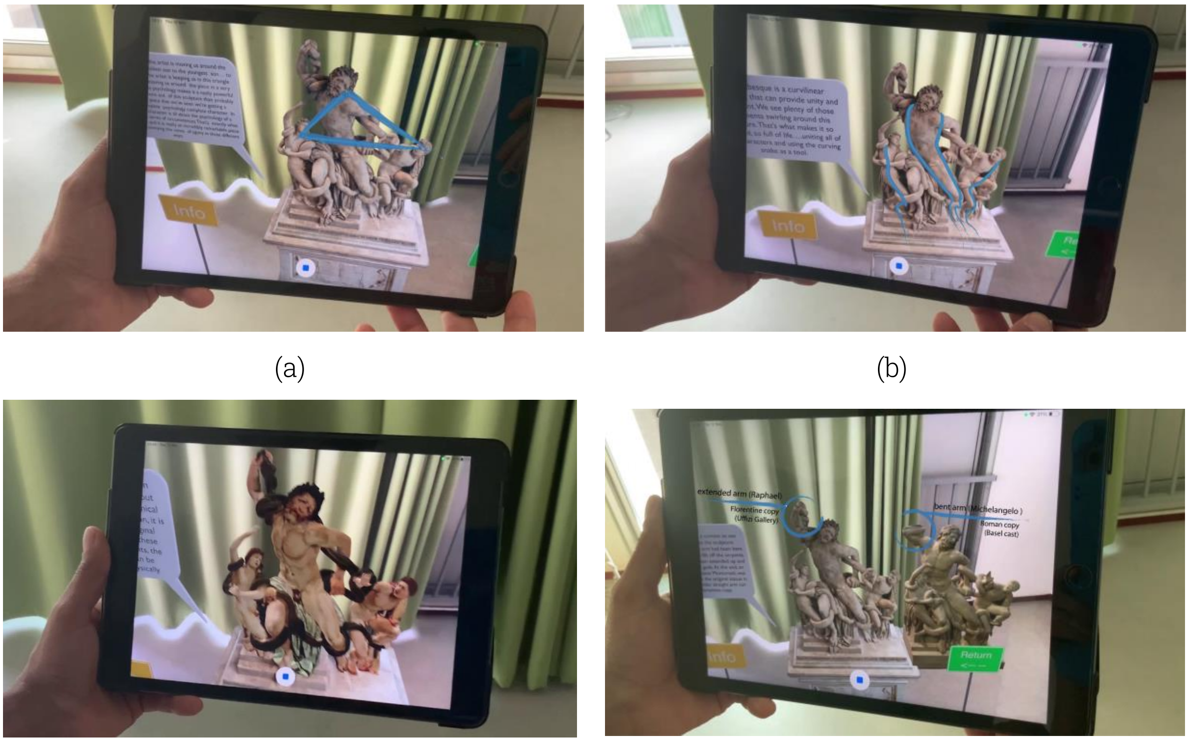
Figure 5.3. 3D model of Laocoön and His Sons anchored to the ground in the digital environment with four exploratory tabs. The model can be projected onto a physical environment by using an iPad or iPhone.

The style tab (Figure 5.4a) transfers the user to a place where he/she can learn more about the unique artistic style of the statue by comparing it with other similar ancient masterpieces.

[28] https://developer.apple.com/augmented-reality/tools/

Furthermore, the style tab has the ability to highlight some important details of the statue through 2D animations.

The dynamics tab (Figure 5.4b) makes the user focus on the sense of movement present in the sculpture through its composition and how many statues of the Renaissance were inspired by such style.



(a) (b) (c) (d)

Figure 5.4. Laocoön and His Sons presented through a mockup AR application with audio descriptions, and written panels in four sections: (a) the style tab; (b) the dynamics tab; (c)the color tab; (d) the comparison tab.

The color tab (Figure 5.4c) superimposes digitally created colors over the 3D model in an augmented environment. Several physical investigations and technical imaging with different types of radiation have made it possible to find and reconstruct the remains of original colored pigments on the surfaces of the statue. Based on this color information, the original colors could be reconstructed both digitally and physically. Even though no colors were found by polychromy analysis performed on this statue, for the purpose of this research and to demonstrate the effectiveness of the technology, the colored sculpture presented in this application was based on an artistic representation of the Laocoön group in a painting by a Florentine painter Alessandro Allori in the 16th century.

The comparison tab (Figure 5.4d) is meant to create a narrative by comparing this reproduction made in the Renaissance with a 3D model of the original version of the Roman sculpture. Through this comparison and interactive storytelling, the user could learn about the history and lifecycle of the statue: the discovery of the Roman statue in the 16th century, restoration, and the several copies of the statue created during different periods in time. All of these tabs had integrated text instructions and audio narratives.

Finally, the digital model of this statue was slightly altered so that it could be 3D-printed in full color at a scale of 1:10. Additionally, the most important features of the sculpture, i.e., the heads of Laocoon and his sons, were then printed on a scale five times larger than the 3D print of the complete statue (Figure 5.5).

Figure 5.5. 3D prints of the sculpture in high resolution and full colors produced by scaling up and down some important features.

These features were placed on a stand that was made to mimic the composition of the statue. By doing so, different possibilities of interaction with physical 3D replicas were demonstrated to the users. The technology used for 3D printing was Colorjet sandstone printing.[29]

Video on digital screen: Narration through the digital screen display

An additional project familiarized the participants with showing a video on a digital screen without any (direct) user interaction. In this video, the viewer was guided through the steps, procedures, methodological approaches, and workflow for diachronically reconstructing a lost monument, i.e., a late Roman circus in the city of Milan (CHT2 project – see chapter 3).

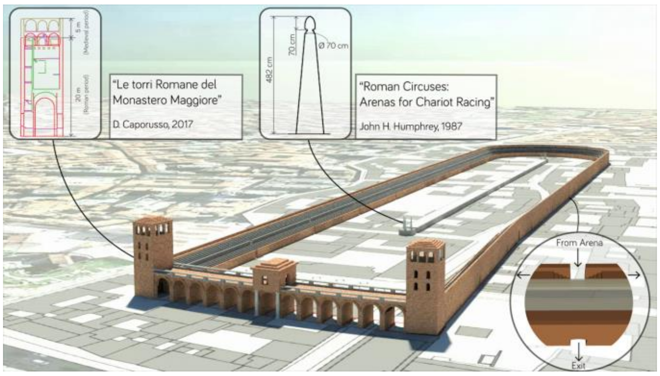


Figure 5.6. A snapshot of the video representing the data integration from different sources for reconstructing a lost Roman circus in Milan presented on a digital screen.

Storytelling through virtual reality application

The second additional application ran on a VR headset, making it possible for the users to visit and explore a place inaccessible to them in reality. The selected project is the Last Super Interactive (LSI project – see chapter 3).

Figure 5.7. Visitors during the LSI immersive experience in Deep Space 8K, Ars Electronica (Festival of Art, technology, and society), September 2019, Linz, Austria.[30]

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[29] The printer used was a ProJet CJP 660Pro - an industrial full-color 3D printer with a resolution of 600 x 540 dpi made by 3D Systems. https://www.3dsystems.com/3d-printers/projet-cjp-660pro
[30] https://ars.electronica.art/center/en/exhibitions/deepspace/

5.2.2 Methodology

The goal of this study was to provide a useful basis for designing interactive experiences through 3D reproductions of CH. For this reason, various data were collected through a collaborative workshop involving all the stakeholders of this project. The collected data include user experience with 3D reproductions, the interaction between user–object–reproduction, the perception of various 3D reproduction methods, the existing practices within the field, new approaches for the use of various reproduction methods, and the implications of these technologies' introduction into the fields of art and CH. The initial proposal was to organize a workshop for the stakeholders. This was planned by hosting several activities that included (physical) interaction of participants with the 3D reproductions as described above and the collection of data through creative sessions and recordings of conversations and discussions. However, owing to the restrictions imposed by COVID-19, the workshop had to be held online.

Stakeholders

A total of 27 stakeholders with different backgrounds were invited to participate in the workshop. Based on their experience and specialties, the participants were divided into four groups, each with at least six people. Given the fact that the workshop was held online, it was possible to invite more people from different backgrounds. The four groups of participants with their specialties/backgrounds are reported in Table 5.1.

Table 5.1. List of participants of the workshop with their background.

Designers (Group 1)		Art historians / Archeologists / Museum professionals (Group 2)		Digital application experts / Engineers (Group 3)		Museum visitors (Group 4)	
1	Color design researcher	1	Art historian	1	3D applications researcher	1	Arts student
2	Design education researcher	2	Museum studies researcher	2	Professor of reverse engineering	2	Art dealer
3	Senior lecturer in Design	3	Lecturer in art history	3	Digital museum exhibitions researcher	3	Computer scientist
4	Museum experience researcher	4	Museum Professional	4	Professor of 3D printing for arts	4	Urban science researcher
5	Industrial Design graduate	5	Museum innovation Professional	5	Digital heritage Researcher	5	Architecture researcher
6	Interaction Design researcher	6	Digital archeology professor	6	Digital applications student	6	Architecture researcher
		7	Art restorer	7	3D printing professional		
		8	Art restorer				

Pre-workshop meetings

Just as the participants differed in age, background, and experiences, they differed also in their knowledge of 3D reproduction methods and their use. Therefore, they were invited to individual introductory meetings (lasting 30 to 45 minutes each) before the actual workshop took place. The purpose of these meetings was to maximize the efficiency of time available during the workshop by preparing the participants for the topic of discussion and their mutual collaboration using online platforms. During these meetings, the participants were introduced to Miro – an online visual collaboration platform for teamwork.[31] They were provided with guidelines for collaborating in teams using this platform.

The different ways of presenting CH via 3D reproduction methods (section 5.2.1), were also demonstrated during these preparatory meetings. As the workshop was organized online, the participants could not physically interact with the 3D artifacts. Therefore, the pre-recorded videos of the researchers interacting with digital applications (AR, VR, digital screen displays) and 3D printed models were shared with all the participants. This way, they had the opportunity to view and analyze them before the workshop.

After the introductory meeting, the participants were asked to sign a digital form of consent, as the discussions were recorded for later analysis. They were also asked to fill in a questionnaire before the workshop. This questionnaire consisted of eleven questions that could be answered by scoring on a scale of 1-5, in which 1 signified *least likely* and 5 signified *most likely*. The questionnaire's purpose was to understand the general interest of the participants in 3D replicas presented through both digital and physical means. The questionnaires also helped to analyze and understand the opinions and perceptions of participants on the proposed uses of 3D reproductions based on their experience of the introductory meetings before the workshop commenced.

Workshop format

During the workshop, all participants were simultaneously connected via Miro and Zoom meetings.[32] In order to invite enough people to participate and hold their attention during the workshop, the total time for the workshop was set to two hours. The time was divided into an introductory session, two collaborative sessions with a five-minute break between them, and concluded with a wrap-up and general conclusions. The introductory session lasted 15 minutes and included the individual introduction of the researchers, an introduction to the format of the workshop, the aims and goals of the activity, an overview of the research questions, the methodology for evaluating the collected data, and a brief introduction of the four groups of participants. In this first session, the participants were also informed about how the results were to be published afterward and the way they could access them.

The first collaborative session (lasting 15 minutes) was designed to quantitatively analyze different scenarios in the fields of art and CH for which 3D reproductions could be used through different methods (AR, VR, digital screens, 3D printing). Without dividing the participants into groups, everyone was asked to fill in at least four sticky notes (one of each color) on the Miro platform (Figure 5.8). The sticky notes were color-coded based on the purpose they served (blue = art conservation, yellow = education, green = museum presentation, pink = research/exploration, orange = other). On each sticky note, one could describe a method for using 3D reproductions and a scenario in which they thought the chosen reproduction technology could serve the purpose. The participants could fill in as many sticky notes as they wanted, with a minimum of 4 (1 art conservation, 1 education, 1 museum presentation, 1 research/exploration); the orange sticky notes were, of course, optional. Before the start of the first session, instructions were given to the participants about what was expected of them and how they ought to fill in the sticky notes. These

[31] https://miro.com/

[32] https://zoom.us/

instructions, along with a few examples, were also written on the collaborative Miro board so the participants could consult the instructions at any time during the session.

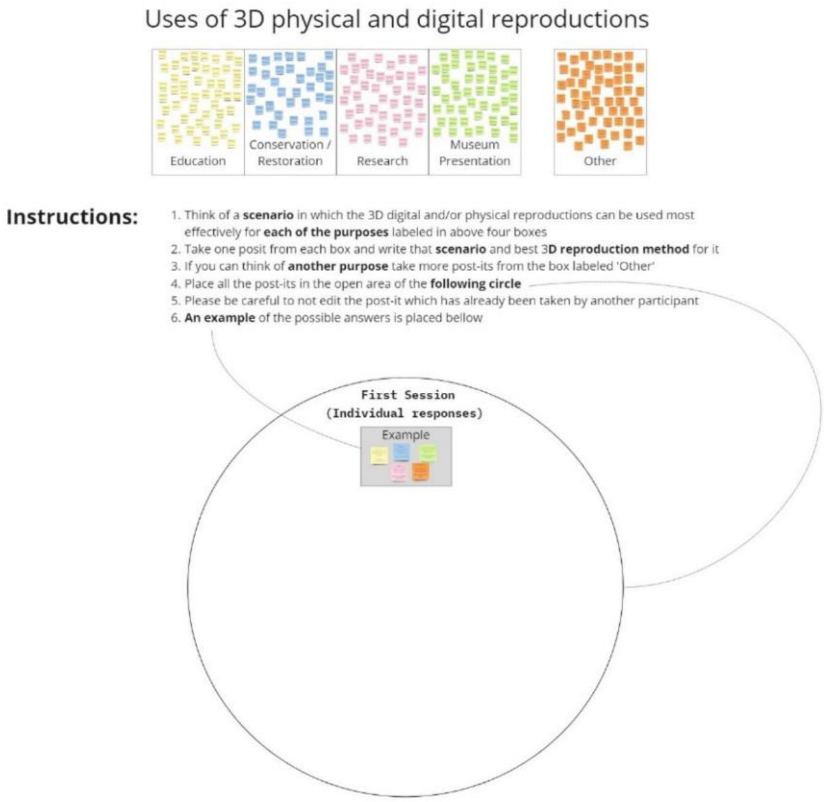


Figure 5.8. The collaborative board of the first session on the Miro platform. The sticky notes representing different uses of 3D reproductions in five colors could be picked from the boxes at the top, filled, and pasted in the empty space provided in the circular area at the bottom. The instructions for filling in the sticky notes are in the middle, along with an example of pre-filled sticky notes.

The second collaborative session lasted 55 minutes and consisted of discussions between the members of each predefined group about how to answer the research questions. Each group was assigned a separate collaborative board in Miro (*Figure 5.9*), and all the members of each group were transferred to a breakout room in Zoom. This way, each group had a separate workspace and platform for discussion. The session questions were divided into two parts. One related to the use and design of 3D reproductions, and the other was more related to the authenticity of the experience (of the original) through such reproductions. Before the start of this session, the resulting sticky notes from the first collaborative session were displayed on the board of each group. Based on the different uses and scenarios proposed through the sticky notes, each group was asked to map their answer using the different templates provided. The use of the templates was not mandatory, and each group had the freedom to decide to use any format or pre-designed map to propose their answers. Similar to the first collaborative session, these instructions were written on the Miro board above the workspace and could be consulted during the session. All four breakout rooms in Zoom in this session were moderated by four moderators, whose role was to clear up any uncertainties in the groups, record the conversations, and foster discussion among the group members.

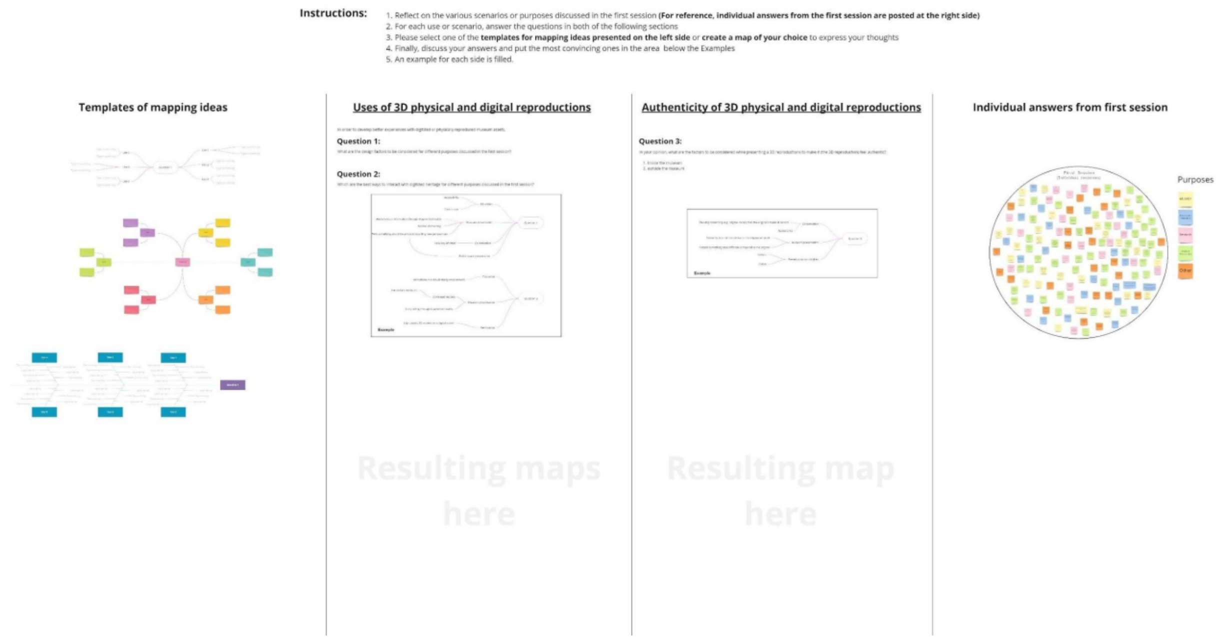


Figure 5.9. The collaborative board of the second session on the Miro platform. Templates for mapping the answers to the research questions are provided on the left side while the middle space is for answering the research questions. The sticky notes resulting from the first collaborative session could be consulted from the left side. The instructions for answering the questions are provided at the top and an example of possible answers for each question is to be found in the boxes below the questions.

The plenary wrap-up session lasted 30 minutes. During this session, the representative of each group presented a five-minute summary of the discussions that occurred amongst the group members together with their results and conclusions formulated during the second collaborative session. Based on these group presentations, the participants were invited to ask questions and share their thoughts for the next 10 minutes. The session ended with a five-minute presentation in which the organizers provided an overview of the activities carried out during the workshop, the way results would be compiled, and how participants could contact the organizers if they had any further questions.

Evaluation

Using the existing literature together with the data collected through the workshop, both quantitative and qualitative data research could be carried out (Figure 5.10). The project resulted in four main sources of data: (1) the answers to the closed questionnaires; (2) sticky notes from the first collaborative session in which different scenarios and possible uses of 3D reproductions were described; (3) mind maps from the second collaborative session in which the participants' thoughts on the applicability of 3D reproductions for enhanced experiences were recorded; and (4) transcripts of the audio recordings of the conversations and discussions during the workshop.

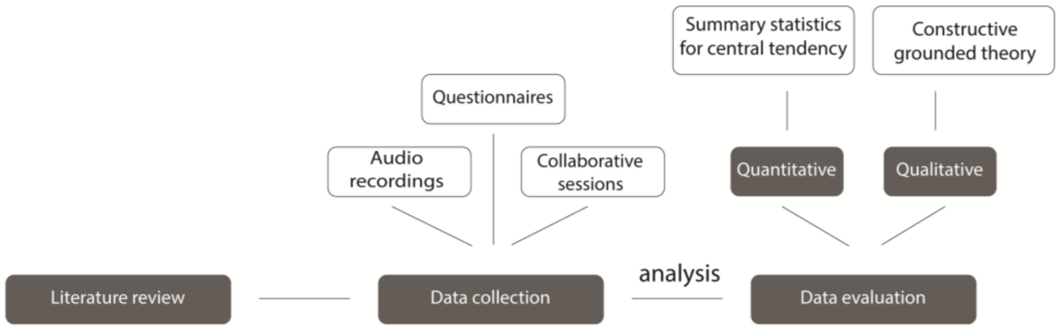


Figure 5.10. Data collection and evaluation pipeline.

5.2.3 Quantitative analysis

The data collected from the pre-workshop questionnaire and the first session of the workshop were analyzed using summary statistics for central tendency (mean, mode, and median method). This analysis was used to partially answer the questions no.1 and 2 of this section of the research:

- How are the 3D reproduction methods under study perceived?
- In what way can 3D reproduction methods contribute to the experience of CH objects and artworks for museum education, CH research, conservation/restoration, and museum presentation?

Raw analysis

Questionnaire

The questionnaire was presented to the participants (n=24) before the workshop and consisted of 11 closed questions. Each participant was asked to rate the answers in a range of 1 to 5, 1 being the least effective and 5 being the most effective. The results of questionnaire responses presented here are based on the mean (m) values and percentage of participant responses greater than or equal to 4 (≥4) i.e. highly effective.

The majority of the participants considered the use of reproductions, whether physical or digital, (very) useful for a variety of art forms (sculpture, painting, architecture, and ethnographic objects (m=4.18, 79% ≥4). Especially in the case of sculptures, the use of reproductions was considered very useful (m=4.46, 92% ≥4). Just as in the previous outcome when a majority of participants were convinced that reproductions were useful for various forms of art, they also considered the use of reproductions (very) useful for four purposes (education, research, preservation, and presentation) (m=4.33, 81% ≥4), particularly when reproduction methods are used for educational purposes (m=4.58, 92% ≥4). When asked about the use of 3D reproduction methods under study (AR, VR, digital screen displays, and 3D printing) for different purposes, the majority of the participants considered all methods of reproduction effective for all four purposes (m=3.83, 65% ≥4), especially 3D printing (m=3.94, 69% ≥4).

The participants were also asked about the effectiveness of reproductions: (1) in the presence of the original artwork; (2) in the absence of the original artwork, and (3) in the absence of the original artwork, but in the same setting (e.g., in two different museums). Most of the participants considered the second option most effective (m=4.13, 75% ≥4). Furthermore, the participants were asked how they would value different uses of 3D reproductions (as a one-on-one reproduction; showing alternatives of the original [e.g., colors, composition, texture]; or the use of reproduction on a larger/smaller scale). The use of reproductions as a tool to show something different from the original (e.g., colors, composition, texture) was considered somewhat valuable (m=3.75, 63% ≥4).

When asked about the effects of 3D reproductions on the perception of art, the participants thought 3D reproduction would impact their perception of the original artifact/artwork to a moderate/large degree (m=3.38, 52% ≥4). Of all reproduction methods, VR was considered the most impactful (m=3.63, 67% ≥4).

The participants were equally interested in using these technologies at home (m=3.38, 51% ≥4) as they would be in a museum setting (m=3.38, 50% ≥4). Of all technologies, VR seemed to be the reproduction method that was the most preferred for use at home (m=3.75, 67% ≥4). In the case of a museum setting, although the mean preference for AR was as high as VR, more participants preferred AR (m=3.58, 63% ≥4).

First plenary setting: sticky notes

In total, there were 116 sticky notes that had been filled in, of which 41 were focused on museum presentation, 23 on education, 19 on research, 17 on other purposes, and 16 on art conservation. Based on the sticky notes, in the case of museum presentation, the scenarios in which 3D technology seemed to be the most captivating were: immersion/simulating what it would be like to be in the setting of the artwork/time travel (6/41, AR/VR); depiction of artworks in different states/times in history (6/41, AR/3D printing); accessibility for the visually impaired and children (6/41, AR/3D printing); showing objects that have been lent (5/41, AR/VR/3D printing). Other scenarios revolved around the recreation of manufacturing processes, lost artifacts, and original settings of artworks (9/41, AR/VR/3D printing). The most mentioned reproduction method was 3D printing (19/41).

In the case of education, the most recurring scenarios were: opportunity to compare distant sites/objects and remote interaction (8/23 AR/VR/3D printing); interaction with artworks (4/23, VR/3D printing); introduction of heritage to young children (4/23, Digital reproduction/3D printing/AR/VR); enhanced immersion/experiencing events (4/23, AR/VR). For education, the participants were of the opinion that all technologies were useful. The most mentioned technologies were AR & VR (15).

For exploration and research-related purposes, the participants mentioned two scenarios that were of primary interest: placing objects in their current/original location to get a better understanding of the original setting (4/19, AR/3D printing) and exploring different perspectives of existing heritage (e.g., polychrome, multiple versions, different shapes, different states of decay, different product design) (4/19, AR/3D printing). Other reoccurring themes and scenarios were focused on the materialistic qualities of artworks (e.g., the visualization of hidden elements, manufacturing process) (6/19 AR/3D printing/Digital reproduction). 3D printing was most often mentioned (12/19).

Analyzing the sticky notes concerning 3D technologies' utility for conservation purposes revealed four major themes: replacement of missing parts (3/16, 3D printing); the recreation of original state and colors (3/16, 3D printing/AR/VR); documentation of current material state/status report/entire collections (3/16; digital reproduction/3D printing); discovering inaccessible/damaged sites (3/16, AR/VR). For this purpose, all technologies were mentioned. However, again, the most mentioned technology was 3D printing (11/16).

Amongst the sticky notes with "other" there was a variety of answers, yet, there were two scenarios that were both mentioned four times: public awareness (AR/VR/3D printing) and marketing: attracting visitors/ selling replicas (AR/VR/3D printing). The opportunity of showing works of art in their original context and creating a more immersive experience was also mentioned as an important opportunity for the use of these technologies (6/17). Other scenarios mentioned were: art market (viz., visualizing how the art would look in one's home or gallery); physical therapy, and security training and training people on how to transport artworks. Of all the technologies, VR was mentioned most often (12/17).

Overall, based on the sticky notes, 3D printing (68/116) seems to be the most preferred reproduction method for all purposes, followed by AR (55/116), VR (53/116), and digital screen displays (11/116).

Discussion

The evaluation of quantitative data about applications of 3D replicas presented here is based on the collective perception of all participants without analyzing their data individually on a personal or professional level.

Overall, the majority of the participants considered the use of reproductions (either physical or digital) (very) useful for all of the purposes included in this research (education, research, conservation/restoration, and museum presentation). 3D printing was seen as a more appropriate method for museum presentation than were digital reproductions, AR, and VR. The latter were considered especially valuable for more explorative and research-driven purposes. Nevertheless, the participants thought that the use of reproductions can add value to the original whether present or not. The use of reproduction technologies was seen as most useful when the original artwork is not in the presence of the reproduction or near the reproduction. For the use of reproductions, it appeared that the participants saw the most potential in reproductions that show something different than the original (e.g., colors, composition, texture). In regard to these technologies' effect on perception, the participants agreed that 3D reproduction could impact their perception of the original artifact/artwork. Of all methods, 3D printing was considered the most impactful. As for the setting, the participants were as interested in using these technologies at home as they would be in a museum setting. At home, the participants preferred reproductions using VR, while AR was preferred in a museum setting.

Furthermore, in the case of museum presentations, the possibility of immersion and the capability of showing what it would feel like to be in the setting of the artwork, the depiction of artworks in different states/times in history, and accessibility for blind people and children were seen as the reproduction technologies' most interesting side benefits. Also, for education, immersion was seen as an important asset. The opportunity to compare distant sites and objects, the possibility to promote remote interaction and the opportunity of introducing heritage to young people was also seen as a welcome extra benefit of reproduction technologies. Regarding exploration and research, there were two recurring scenarios: placing objects in their contextual/original location and the exploration of different perspectives of existing heritage. Analyzing the results for using technology for conservation purposes showed that the technologies were regarded as most useful for replacement and recreating missing or damaged elements of CH objects and as a tool for material documentation. Additionally, the technologies were regarded as useful for stimulating public awareness, either as a tool for people to better comprehend the fragility of CH or as a tool for museums and cultural institutions to promote their collections and ethos. Overall, 3D printing appeared to be the most preferred technology for all purposes.

5.2.4 Qualitative analysis

While quantitative data can be used for descriptive overviews or for testing hypotheses, qualitative data can provide a richer understanding of quantitatively measured data. In social sciences, Grounded Theory (GT) is a popular qualitative research method. It allows one to collect data from a variety of sources such as interviews, focus groups, group discussions, and participant observations. Data are co-constructed by the researchers and participants and coded by the researchers' perspectives, values, privileges, positions, interactions, and geographical locations [Charmaz 2009].

Mainly applied to social sciences, GT has gained wide acceptance in various other domains. Specifically, within Human-Computer Interaction (HCI), GT has been found to provide qualitative insights into understanding how usability issues are subjectively and collectively experienced and perceived by different user groups [Adams et al. 2008]. Moreover, several problems in User Experience Design areas are likely to have few existing theories to fall back upon and the context in which the experiences occur plays a crucial role. GT can be a potent tool for generating new knowledge [Khambete and Athavankar 2010].

In order to comply with this study's aim of getting insights into designing and enhancing experiences with 3D technologies and to evaluate the perception of these CH reproductions, a simplified approach drawn from GT was adopted to analyze the qualitative data collected during the collaborative sessions. The data were collected through mind maps and recordings of the conversations. These were analyzed through a constructivist GT approach [Charmaz 2014]. Insights gained from the literature review, transcription of audio recordings of participant discussion during the workshop, and mind maps from each group of participants during the second collaborative session were analyzed by this approach (*Figure 5.11*).

The analysis started with individual memo writing, which involves writing down thoughts, feelings, or questions that arise from the analytic process by two researchers separately. Subsequently, the memos were analyzed by coding based on the relevancy of concepts and the similarity between them. As different groups approached the same questions in unique ways, the analysis was made in context i.e. the background of the participant and the groups.

During the data coding phase in a qualitative evaluation, properly dealing with inter-rater reliability is highly recommended to avoid a large influence on the quality of data evaluation by the researcher's biases [Armstrong et al. 1997]. Therefore, key concepts implicit in each of the groups were articulated and refined simultaneously by two researchers working in isolation from each other. Finally, their results were compared in order to pinpoint the most prominent concepts and themes.

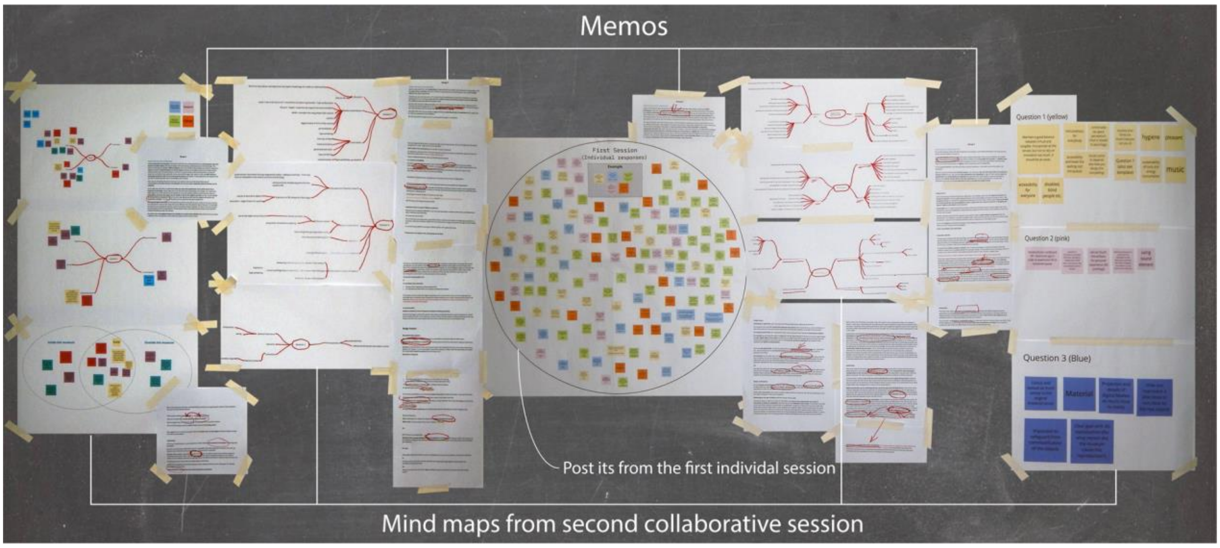


Figure 5.11. Analyses of the qualitative data from collaborative sessions through Grounded Theory.

Overview of group discussions

This section reflects upon the observed differences among the four groups in ways of understanding and approaching the same questions. These observations were later used to draw the evaluation criteria from data in context (section 0).

Understanding of questions

The group of designers spent considerable time trying to understand the broader purpose of the questions. It was concluded by them that it was preferable to focus on a specific design goal instead of giving technology a general-purpose since the design of technology depends largely on objective factors. The group of engineers and museum professionals, on the other hand, approached the questions more directly, proposing different solutions to create better experiences with the 3D technologies for all stakeholders. Lastly, the group of visitors understood the questions related to experience design instantly but were thrown off by the question of authenticity. Overall, the concept of authenticity was much discussed in all the groups. They interpreted it in two ways: it could refer to the authenticity of the copy or the authenticity of the experience.

Approach to answering questions

When answering the questions, instead of using a template, the group of designers proposed their own diagram based on the context for the use of technologies and the way the technical aspects and formal aspects of technologies should and could comply with this. The group of visitors approached the questions similarly and did not use a template either, but they wrote their ideas on sticky notes. On the other hand, the group of cultural heritage professionals and engineers did position their answers in the templates. According to the group of engineers, the applications under discussion differed from one another. Therefore, the way they answered the questions was by imagining the best ways to interact with CH objects presented via these different reproduction methods. Here, they made a distinction between policymakers, researchers, conservators, and visitors. They analyzed how the different interactions with objects could be improved by shifting from an analogical way of handling objects to a digitalized/physically reproduced way. In general, they argued that (digital) reproductions are complementary whilst respecting the integrity of the "analog" real artifacts.

Observations from discussions

The group of designers considered different design factors ranging from aesthetics to function. They proposed several factors that should be kept in mind not only for designing experiences with objects but also for designing and managing the 3D content. As for the question related to interaction, they, as well as the group of heritage professionals and the engineers, asserted that the technologies and modes of interaction used should be developed based on the needs of the users. Here, when discussing the authenticity of experience, they discussed authenticity from a user's (visitors and curators) experience perspective. Somewhat similarly, the group of engineers thought that modes of interaction to a large extent revolve around the interaction with physical 3D reproductions; hence their emphasis on authenticity in terms of art's materiality.

In contrast, the discussion among the group of visitors was more focused on the general needs of the visiting public without aiming at design factors specifically. They approached this topic of interaction by relying on their past experiences in museums. In terms of authenticity, like the engineers, they put the most emphasis on physically 3D printing materials and textures.

Criteria for evaluation of experience based on group discussions

The following section, grounded in the data collected from participants, is an attempt to answer the question no. 3 of this part of the research ("what are the design factors to be considered in order to develop enhanced experiences and interactions with 3D digitized and printed CH objects in a museum setting?"). The qualitative analyses of the data collected from the four groups were based on their expertise and resulted in devising a number of evaluation criteria for designing experience, 3D interaction, and authenticity.

Designing the 3D cultural experience

User experience can be considered as the sum of three factors: users' context, the characteristics of the designed system, and the context within which the interaction occurs [Hassenzahl and Tractinsky 2006a]. The analysis and comparison of conversations between different groups during the workshop unveiled that these three design factors are equally important for designing experiences with 3D reproductions (Figure 5.12).

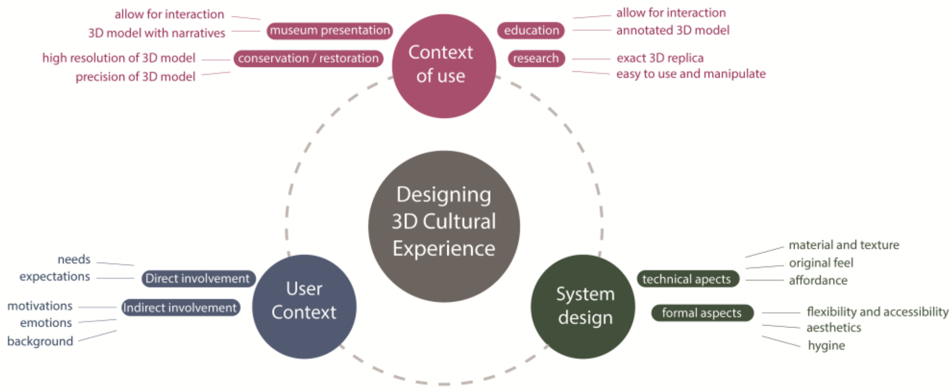


Figure 5.12. Design factors for 3D cultural experience based on evaluation of qualitative data.

Firstly, the context of use was considered paramount in deciding which technologies are or will be used. A 3D model used for conservation purposes should serve as technical support for the artwork, and thus should be very precise and highly detailed. In this case, a fraction of the original artifact, but in a high resolution, is considered more useful than a large-scale model at a lower resolution. For this reason, the high-quality AR model was considered very useful for preservation-related purposes. It can accelerate the process of recognizing small details in art hidden to the naked eye (e.g., recognizing painters' styles through brushstroke analyses or looking into painting samples of different layer buildups). In the case of research-related goals, the 3D model must represent an exact digital replica of the real object that is easy to use, so that even if the researchers are physically apart from the actual CH site or object, they are still able to analyze and manipulate them as if they were handling the actual object. For museum presentation, on the other hand, the precision of the reproduction is not crucial; therefore, a large-scale model at a lower resolution presented with additionally connected narratives was considered to be the most appropriate. It is worth mentioning that museums are not closed spaces presenting their art only inside fixed exhibition spaces, but they have franchises reaching far beyond their physical walls. 3D reproductions can be helpful in designing different strategies in order to bring art to the public [Rijks Museum 2020]. In this way, by using 3D technologies before or after the museum visit, museums could attract more people to the actual physical exhibitions in the museum. Here, people's interests could be triggered by letting them interact with art through reproductions. For education purposes, the annotated 3D models that can be interacted with on a digital screen were considered highly effective. In brief, the experience must be content- not technology-driven.

Secondly, based on the analysis of collaborative sessions, the target groups for designing experiences with 3D models can be divided into two branches: people working directly with the physical work of art or heritage objects (e.g., restorers, researchers, art historians); people not directly involved with art (e.g., museum visitors, educators in schools or museum education units). These two groups have different needs, and the experiences must be designed to comply with these needs. In the case of conservators, researchers, and art historians, exact replication of the artwork is essential. For visitors, 3D models should not just be representative but should also provide an addition such as a narrative that is, above all, functional, easy, fun to navigate, and engaging. This could be done, for example, by focusing on triggering emotions or memories when providing information that is being taught. Moreover, the 3D reproduction methods should be self-explanatory. In this way, confusion and the feeling of being overwhelmed can be avoided, hence saving time whilst securing the efficacy of the learning process. Furthermore, especially within a museum setting, spatial arrangement and the careful curation of visitor streams are of utmost importance when considering the use of 3D reproductions. For example, in an exhibition with digital screens, it often happens that there is a long queue of visitors that are waiting to use them. Here, considerations could be made on installing more screens or re-routing the visitors to other parts of the exhibition to avoid crowding.

Thirdly, apart from formal aspects of system design (e.g., aesthetics, hygiene, flexibility, and accessibility), technical aspects of designing the experience were prioritized. It appeared that 3D reproductions - especially 3D prints - can contribute to an extra dimension for the visitor: touching artifacts. By giving the general public the possibility to touch the artwork through 3D printed replicas, we can evoke the same feeling as experienced by restorers or art historians who can touch the real artwork on a daily basis, making it possible to come closer to it and its creator than ever before. In this case, for reproductions to be effective, they should not only look like the original, but most and foremost, should *feel* original: the print's texture, temperature, shape, and weight should be similar to that of the original. For example, in Boijmans van Beuningen's *Sgraffito in 3D exhibition* [Museum Boijmans 2009], 3D printed reproductions of plates were placed in front of the original artifacts, giving the visitors the opportunity to experience the original artwork. On the other hand, technologies using digital 3D replicas must be made comprehensible for users by carefully designing the affordance of digital applications. Such applications must be easy to use also for professionals (who are generally reluctant to use new methods instead of the traditional techniques) for creating reliability.

Interaction with the digitized artifacts

When asked about the modes of interaction with 3D replicas (3D printing, AR, VR, digital screen displays), all groups asserted that the interaction tools must be selected based on the needs of the stakeholders and the goals of the museums (*Figure 5.13*).

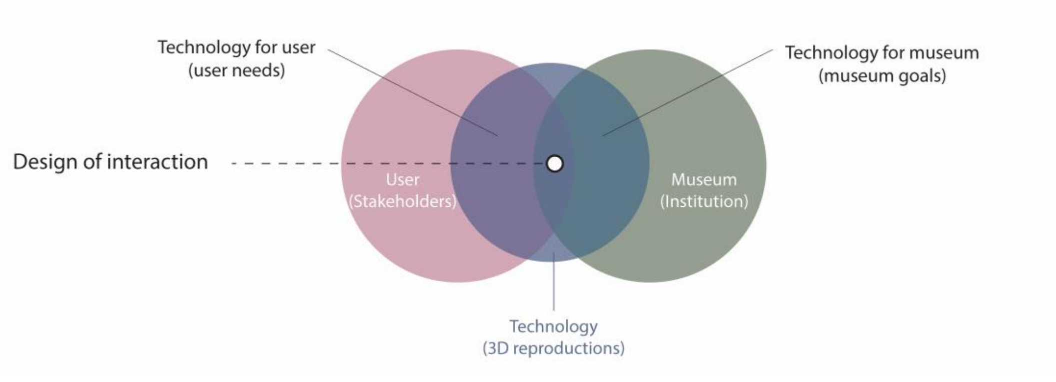


Figure 5.13. Criteria for interaction with 3D replicas of CH based on evaluation of qualitative data.

In terms of interaction with users, the details of each case make it hard to determine in advance the efficacy of 3D reproduction methods. Clearer to define, however, is approaching the way 3D technologies can facilitate the day-to-day practice of stakeholders that interact with CH objects. For example, interactive 3D models could support restorers and researchers to make material analyses easier and faster. Such simple interaction can be created by using a digital screen display.

A similar approach can be adapted for other purposes. Questions that can be asked for instance, for education is to what extent 3D reproductions can contribute to what is being taught? For restoration: should 3D printed parts stand out within the lost composition, or should they be fully integrated into the context? In the case of museum presentation, one must make decisions based on the objective of showing a reproduction, which will determine to what extent a reproduction should stand out as being a reproduction. For museum visitors, the most effective way of creating interaction with 3D technology is to narrate stories that provide a more profound dimension to the museum experience that offer something new. For example, using VR makes it possible to generate a sense of time travel and link this to the museum's collection. Although this method can be used both inside as well as outside of the museum, it is advantageous inside of the museum where the artwork is mostly not in its original context but still provides a tacit link between visitor and artwork. In the history of art, historical evidence or archaeological environments are generally explained by showing the artifacts in 2D or by showing fragments (e.g., a shard from a vase) or fragmented information. Here, 3D reproduction could be useful to add three-dimensionality, but it can also contribute to the object's context (e.g., showing the shard within the entire shape of the vase). AR applications were considered most suited for these digital interactions with physical objects.

Apart from the users' perspective, the participants agreed that 3D technologies are mainly interesting for museums as tools to offer possibilities for doing something that is impossible in physical reality. For example, museums can create emotional interactions with the visitors, something that might not exist in the normal presentation with a label next to the presented artwork. In this case, museums need not to create interactions that can make the existing practices better but can offer something new and completely different from previous experiences. For this reason, something that is immersive like VR was considered to be the best option. Yet, it was mentioned that for practical reasons, it could be complicated to use VR in a museum with thousands of visitors on a daily basis. Furthermore, the use of headsets in museums can create problems of hygiene or financial concerns for the multiplication of the tools that are needed for every visitor to interact in an immersive way.

Furthermore, including physical 3D printed reproductions and the option for the visitors to touch them can contribute to making museum content more accessible to a wider audience (e.g., blind or partially sighted people). As mentioned before, here, materiality is important and a hurdle to be overcome as the 3D print's plastic or resin does not come near the materialistic feel of a marble statue. For instance, one of the participants mentioned that using 3D reproductions for blind or partially sighted people is tricky as a replica alone is not sufficient. In a workshop held in 2015, paintings by van Gogh were presented amongst spectral maps and a real sunflower for people to feel the shape of the sunflowers. Only in this way did the 3D reproduction contribute to helping blind people understand these abstract artistic concepts. Besides its potential usefulness for aiding visually impaired people, touching a work of art also adds the possibility of seeing and touching artistic or cultural objects that are inaccessible, too fragile to display, being restored, or stored in museum depots. With 3D printing, museums can have an exact facsimile to help show how these objects were originally used, and visitors can actually have something approximating the "original" experience by touching them. The same goes for 3D printing fine art such as paintings. Feeling different layers of a painting can contribute to understanding the artwork's dimensions and the artist's techniques.

The authentic experience

Authenticity is a complex and heavily debated concept within the field of art and cultural heritage, especially since the ICOMOS' NARA document on authenticity was published in 1994 in response to the need to better define this idea [UNESCO et al. 1994]. Nowadays, "authenticity", as seen from a Western perspective, could be described as something that has the quality of being authentic, original, or genuine [Latour and Lowe 2012]. It refers to something that is genuinely made or done in a traditional way that faithfully resembles an original based on reliable facts [Tissen 2020]. With the term authenticity, one often refers to the material of the original artwork as the only provider of the true traces of the past and a connection with the artist. However, in the same text and in other recent studies on the authenticity of CH objects and the interference of 3D technologies, it became clear that authenticity does not solely rely on singular and static materialistic qualities of art, but rather relies on a complex system of contextual and conceptual meaning and significance granted to the object. The material of an object, together with these different perspectives, creates the irreplaceable value of an artwork: its authenticity [Jones et al. 2018; Jensen 2018]. The latter appeared to be the perception of authenticity among the groups under study: they agreed on the need of defining the term "authentic" or "non-authentic" in a contextual way instead of emphasizing the materialistic qualities of CH artifacts; hence the material/visual similarity of the replica (*Figure 5.14*).

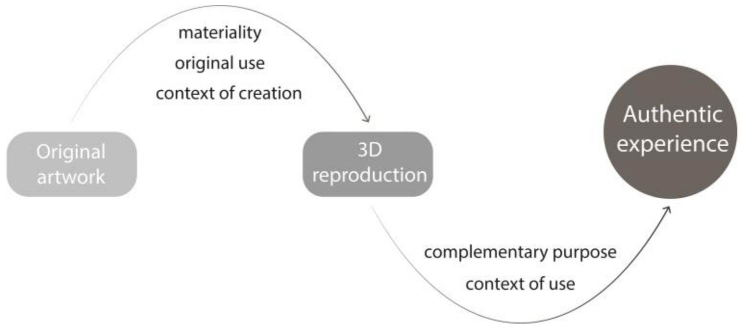


Figure 5.14. Criteria for the authentic experience of 3D replicas of CH based on evaluation of qualitative data.

Additionally, when presenting a 3D reproduction, it was considered essential for the reproduction to be of good quality and as identical to the original as possible. Consequently, in order to avoid confusion, it was said to be important to clearly state that it is a facsimile, as 3D reproductions should always be complementary to the real objects; hence reproductions cannot be compared to their original source. Here, in terms of design, it has become clear that the decisions must be made based on balancing two things: the extent to which we make a high fidelity reproduction and, at the same time, demonstrating that it is actually a copy. Furthermore, according to the participants, authenticity is experienced in multiple ways through our senses: there is a clear difference between seeing, touching, observing, and knowing. Material resemblance or similarity was more often considered important than the visual qualities of the reproduction. Consequently, when designing a reproduction, there are choices that can be made based on either the visual likeness or the "textural/tactual" similarity of the reproduction, depending on the purpose of the reproduction and the specific characteristic of the original it is designed to highlight or enhance. Different technologies have different effects. A 3D print in plastic, for example, never truly resembles the materiality of the original object. However, when considering the use of digital reproduction methods (AR, VR, and digital screen displays), the materiality of the object can not only be reproduced but also be manipulated: for example, reproducing the paintings without a layer to see their original state (incisions made by the artist, etc.) by reconstructing every layer of a painting. In this way, although the materiality and feel of the artwork are not directly physically presentable, the 3D technology provides a new way of playing and interpreting the visual and material authenticity of the original object. The importance of authenticity of the artwork and material, visual or contextual qualities of reproduction in this sense depends largely on the purpose for making and using a 3D reproduction.

When considering the use of reproduction for conservation and research-related purposes, the emphasis is placed on the authenticity of the artwork's material qualities. In this sense, the material feel and appearance of 3D reproductions should remain close to that of the original objects and the feel of those objects. Here, it was said that reproduction can be visually different, as long as the material feel of the reproduction resembles that of the original. That way, a 3D print would be the most efficient for this purpose as it is the only technology that conforms to the necessity for a material authentic experience.

In contrast, when using 3D reproductions for education and museum presentation, the focus on authenticity and the role of reproduction shifts drastically. Whereas it is important for conservation and restoration specialists to remain close to the genuine material of the object (and thus the reproduction), the focus for education is more related to the representation of context and different perspectives, both intangible qualities of art. For the general public, the focus should be on achieving the experience of authenticity rather than the similarity of material. Furthermore, instead of focusing on mimicking and reproducing experiences that can already be done in reality (e.g., visiting museums via virtual tours), the visitors said reproductions are more useful for creating a complementary non-existing experience that is otherwise not possible with the original object, context or (museum) setting. Here, it becomes clear that the importance granted to conceptual and contextual authenticity is key when considering the use of art reproductions. The participants argued that these technologies can be used to create narratives that connect with visitors' personal experiences in ways that are educational, emotional, or intellectual, as long as they enhance the idea and relationship between the visitor and the work of art. Unlike the cases of reproductions used in restoration or research, pointing out the exact difference between the real and the copy is not as important in museum presentations or education. Therefore, 3D reproductions need not be as visually or materially similar. What is essential, however, is creating individual narratives that are authentic to one's personal experience. Yet, this is hard to achieve using solely one reproduction technology, since different people perceive aesthetic works in different ways and have their own set of memories.

To create experiences that conform to individual needs and thoughts, different 3D models, technologies, and immersive sets should be adopted. In the case of authenticity and the role of reproductions in this regard, we have to understand how people perceive the entire process between artwork, (museum) visits, and reproduction for them to stay connected to the masterpiece. This can take place both inside as well as outside the museum, both having different effects. Here, In the case of using 3D reproductions in museum spaces, the use of physical 3D reproduction was considered most effective when it would be demonstrated next to the original artwork because it helps in making comparisons with the original. Here, a direct encounter between original and reproduction was thought to enhance the connection between visitor and art the most, since the museum space itself does not provide any other contextual information about, for instance, the creative process. Outside of the museum, however, other factors are at stake. Depending on when the original object was made, we can present the original object through reproductions near the owners of the authentic objects or their creators, or artworks can be placed in the original building or studio where it was once made. Here, it is not about making a material authentic object or reproduction, but the focus is on getting to know the creative process. The source community can be involved in making objects authentic in terms of experience. Eventually, it all depends on the final experience that is needed and what output a certain project aims at, which is decisive in the choice of the reproduction method to express these aims and the way it is designed. Different perspectives, purposes, and motives determine the authenticity of the experience and the reproduction. On the whole, the participants agreed that reproductions are especially useful for (re)creating context and intangible experiences. They were considered important for meaning-making and offering new perspectives, enhancing the connection between people and the material work of art, and creating new valuable meanings for these objects in society.

5.3 Museum visitor evaluation at Archeological Museum of Milan: PERVIVAL project

For the past three decades, the interactive museum experience model [Dierking and Falk 1992] has been a reference point for researchers in museum experience and visitor studies. This model simplifies our understanding of museum experience by considering it "an interaction that occurs in the personal context of the visitors, the physical context they encounter and social context they experience" for all types of museums and all types of visitors. Similarly, other authors have argued to evaluate the museum experience as a "fit" between visitors' meaning-making and the methods used by museums. Visitors' meaning-making is a combination of visitors' agenda, personal context, and how they create meaning for themselves, rather than passively receiving the content offered by a museum exhibition [Rounds 1999; Silverman 1995]. Subsequently, drawing from literature on tourism, museum, and visitor studies, [Packer and Ballantyne 2016] characterized the visitor experience as: "(i) inherently personal and subjective; (ii) responsive to the affordances of external or staged activities, settings, or events; (iii) bounded in time and space and (iv) significant to the visitor i.e. it has an impact on the visitor that makes it noticeably different from everyday life".

The past visitor theories and museum experience models gave rise to a new relationship between the visitor needs and museum goals in contemporary museum practices. Museums are increasingly working to understand and respond to their visitors' behavior to stay "relevant" [Simon 2016]. Therefore, the museum practices such as audience engagement [Mcintyre 2014; Visser et al. 2013], participatory experience [Simon 2010], collaborative design with visitors and interdisciplinary professionals [Vavoula and Mason 2017; Avram et al. 2019; Ciolfi et al. 2015] and personalization [Raptis et al. 2019; Ardissono et al. 2012] are gaining popularity in recent years.

Furthermore, the literature on such contemporary museum practices highlights the potential of digital technologies in improving the visitor experience and reaching the museum goals. Consequently, museums are increasingly adapting the technological applications in their practices to involve visitors. In 2016, a New Media Consortium Horizon report highlighted the short-term, mid-term, and long-term impacts of emerging technologies on education and interpretation in museums worldwide [Freeman et al. 2016]. The report reveals the importance of emerging technologies to further museums' interpretation goals and enhance their visitor experiences by developing effective digital strategies. Yet, relatively few studies investigate the visitor behavior of interaction with digital museum exhibitions and its effects on their experience and museum goals.

The early visitor studies demonstrated the short and long-term effects of visitors' agenda, motivations, the context of the visit, and interaction in the museum on their learning outcomes [Packer and Ballantyne 2002; Ellenbogen 2003; Stevenson 1991; Falk et al. 2004]. To evaluate the learning outcomes, quantitative and qualitative methods were adopted in these studies. While quantitative data in these studies were collected through simple questionnaires and time tracking of visits, diverse qualitative methods were also introduced in these early studies. Such qualitative methods include ethnographic techniques to understand the culture of learning environments [Brewer 2000], content analysis to identify code and categorize patterns or themes in qualitative data [Bernard and Ryan 1998], and Personal Meaning Mapping (PMM) to measure the effects of a specific educational experience on visitors' personal, conceptual, attitudinal, and emotional understanding [Falk and Dierking 2003; Falk et al. 1998; van Winkle and Falk 2015] and comparison of data collected in various contexts of interaction.

Further studies explored visitors' perceptions of specific types of interactives, the role of interactivity in visitor experience, and visitor behavior analysis for designing interactions. Drawing from the past studies, the researchers employed both qualitative and quantitative methods for the evaluation of visitor experiences for different purposes such as perception of digital and physical reproductions and their effects on museum learning [Lindgren-Streicher and Reich 2007], interface design evaluation [Hornecker 2008], motivation and behavior study of online visitors [Fantoni et al. 2012; Skov and Ingwersen 2014] and evaluation of visitor experience at onsite exhibitions by visualizing visitor flows and preferences in the physical spaces [Strohmaier et al. 2015].

More recently, to evaluate the visitors' digital experience in the museum context, some researchers combined the traditional qualitative data collection techniques such as ethnography, and interviews before and after the interaction with quantitatively tracking the visitors' digital interaction. To provide valuable bases for designing, implementing, and managing digital applications for museums, a few studies were executed to evaluate visitor experience for the following types of digital interactions: digital display systems [Liu 2020], mobile devices in museum settings [Moussouri and Roussos 2015; Roussou and Katifori 2018] and augmented reality/ virtual reality for museum visits [Petrelli 2019].

A comprehensive study to evaluate the design of digital interaction in a museum exhibition (visitor experience) and eventual learning outcomes (museum goal, i.e., education and interpretation) has not yet been executed.

5.3.1 Methodology

This study, starting from the analysis of an interactive digital experience designed for a complex museum collection (CMC), verifies the effectiveness of the narratives designed for the application and assesses the learning outcomes of such applications. The data on visitors' experience and learning was collected based on their interaction with the PERVIVAL application (see chapter 3) installed at the Civic Archaeological Museum within the ambient of the exhibition "Sotto il Cielo di Nut" (Figure 5.15a).

(a) (b)

Figure 5.15. PERVIVAL touch-screen at the exhibition "Sotto il cielo di Nut" in the Civic Archeological Museum of Milan. (a) A group of visitors (research participants) interacting with the application; (b) Interviewing with users of the application at the entrance/exit of the exhibition.

- A mixed-methods approach was used to collect and evaluate data on visitors' interaction with the PERVIVAL application. Three types of data were collected:
- the data on visitors' interaction by recording the application log
- data on learning outcomes through interaction by interviewing the visitors (Figure 5.15b) at the entrance/exit of the exhibition before and after their visit
- the demographic data of the visitors through a questionnaire

Data collection

Although the content analyzed and types of interactive applications in the past studies were not exactly the same as being analyzed in this section, the literature review provided useful insights on data collection and research methodologies for user (visitor) studies. The literature suggests the necessity of collecting both quantitative and qualitative data for thoroughly evaluating visitors' experiences and learning from interactions in the museum context. Several approaches have been employed in the past for quantitative data collection including interaction sequence tracking, visitor time logging, user study surveying, and questionnaire. Instead, the approaches used for qualitative data collection in the past museum visitor studies include PMM, structured/semi-structured/open-ended interviews, follow-up phone interviews after the visits, observations and handwritten notes by the researcher, and open conversations with the visitors. Furthermore, collecting the demographic data of visitors is considered important to analyze the collected data in context. This can be done by either questionnaire or a baseline interview.

For in-depth analysis of interaction and learning aspects of visitors' interaction, the literature suggests the data collection before, during, and after the interaction and not informing the visitors about the purpose of the study in order to collect unbiased opinions.

Most of these aspects of the data collection were covered by carefully designing a protocol of semi-structured Interviews, interaction logging, open-ended questions, and closed questionnaire. This data was then integrated with the physical observations taken by the researcher during the visitors' interaction with the application (Figure 5.16).

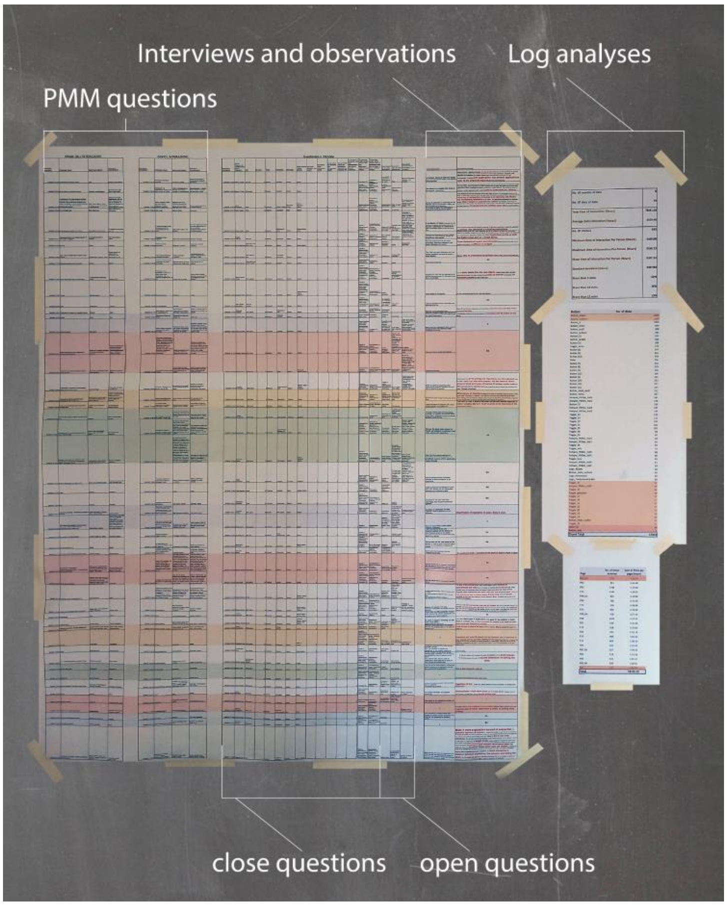


Figure 5.16. Different types of visitor data collected before, during, and after the interaction.

For each interaction with the application, an automatic log entry was generated which included the time and type of interaction for each visitor. Apart from the log information, a total of 50 visitors (the research participants) who interacted with the PERVIVAL application were also interviewed. Most of the research participants had no to limited prior knowledge of 3D technologies applied to the museum context. The interview protocol was designed on the principles of "Personal Meaning Mapping" (PMM). Before the interaction, the visitors were asked questions about their knowledge of the content that was being delivered by the application. The same questions were repeated after the interaction and the answers were connected with the log information to analyze the learning aspects of the interaction. This activity provided several insights on the importance of designing the interaction based on the type of content (3D or otherwise), selection of narratives, and interrelation between the content type and narrative.

In the end, the participants were asked to fill in a questionnaire. The questionnaire consisted of two parts. The first part aimed at collecting the demographic information of the visitor (age, sex, profession, interests, etc.) for analyses of the interviews in context. Furthermore, as anticipated, half of the participants in this research did not feel comfortable answering the questions verbally. Therefore, the second part of the questions consisted of 2 closed and 3 open questions to understand their opinion and assessment of different aspects of interaction with the application.

The participants of the research were divided into two groups based on their background: (a) expert visitors were those who were already familiar with the subject and had already experienced other similar digital applications for archeology and (b) inexperienced visitors were those who had either none or very few experiences of the subject. They were also divided based on how they interacted with the application i.e. sole visitors and Group visitors.

Evaluation

Among several methods for data evaluation, the most coherent methods with the type of data collected for this study were adopted for evaluating the visitors' interaction and learning outcomes. The quantitative data collected in form of interaction logging and a part of the questionnaire were analyzed through summary statistics for central tendency and meaning-making through visualizations. The qualitative data collected through interviews and physical observations were analyzed through content analysis [Mayring 2015] of pre-interview and post-interview responses and of the visitors.

5.3.2 Application Logging

To analyze the visitor interaction with the application and to verify the effectiveness of the narratives designed for the application, the log information of the application was recorded. The log created an entry for each interaction on the screen (Figure 5.17). Each log entry included the following data:

- time and date of the interaction
- name of the page on which the interaction occurred
- type of interaction (tapping a button, moving a slider, zoom in/zoom out)

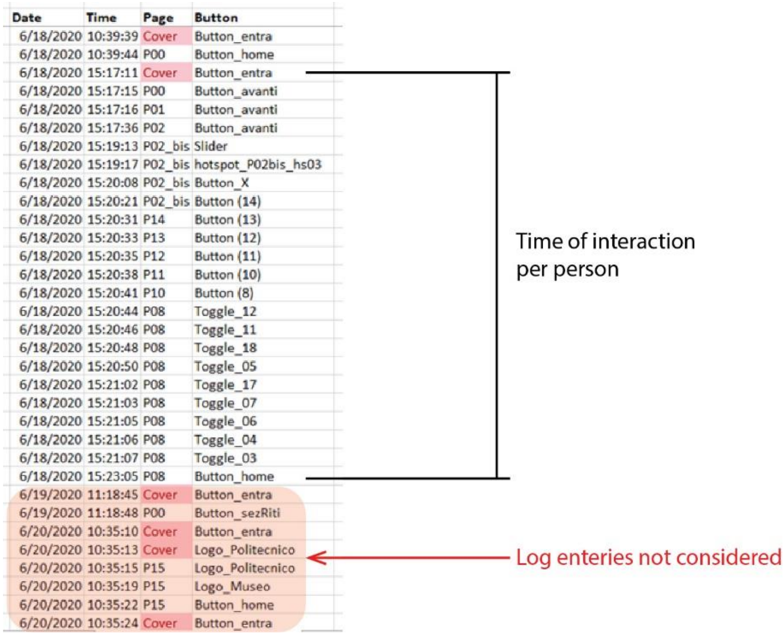
Such data were collected for 73 days over a period of 5 months (6 working days for 2 months, only weekends for 3 months). In this period a total of 4,532 visitors entered the exhibition hall where the PERVIVAL application is installed.[33] The log data was then analyzed for:

- minimum, maximum, and average time of interaction per person
- most and least interacted pages
- most and least used buttons
- the visitors' path of interaction

For calculating the time of interaction per person, it was necessary to identify a singular person from the available log information. Even if there was a button on each page to finish the interaction and return to the homepage, most of the visitors did not return to the homepage after finishing their visit. Furthermore, several passing-by visitors just tapped the screen without having real interaction with the application. Therefore, the log data was filtered first to remove such anomalies. An example of calculating the time of interaction of a particular visitor and the

[33] The data on total number of visitors of the exhibition was provides by the civic archeological museum of Milan.

misrepresenting entities is presented in Figure 5.17. The time of real interaction of visitors with the application was calculated by highlighting all the log entries containing the cover page. The time of such entries was then subtracted from the time of the entry prior to the next interaction on the cover page. The entries in which the interaction at the cover page was repeated or very near to the preceding entry (less than 5 seconds of time difference) were ignored.



Date	Time	Page	Button
6/18/2020	10:39:39	Cover	Button_entra
6/18/2020	10:39:44	P00	Button_home
6/18/2020	15:17:11	Cover	Button_entra
6/18/2020	15:17:15	P00	Button_avanti
6/18/2020	15:17:16	P01	Button_avanti
6/18/2020	15:17:36	P02	Button_avanti
6/18/2020	15:19:13	P02_bis	Slider
6/18/2020	15:19:17	P02_bis	hotspot_P02bis_hs03
6/18/2020	15:20:08	P02_bis	Button_X
6/18/2020	15:20:21	P02_bis	Button (14)
6/18/2020	15:20:31	P14	Button (13)
6/18/2020	15:20:33	P13	Button (12)
6/18/2020	15:20:35	P12	Button (11)
6/18/2020	15:20:38	P11	Button (10)
6/18/2020	15:20:41	P10	Button (8)
6/18/2020	15:20:44	P08	Toggle_12
6/18/2020	15:20:46	P08	Toggle_11
6/18/2020	15:20:48	P08	Toggle_18
6/18/2020	15:20:50	P08	Toggle_05
6/18/2020	15:21:02	P08	Toggle_17
6/18/2020	15:21:03	P08	Toggle_07
6/18/2020	15:21:05	P08	Toggle_06
6/18/2020	15:21:06	P08	Toggle_04
6/18/2020	15:21:07	P08	Toggle_03
6/18/2020	15:23:05	P08	Button_home
6/19/2020	11:18:45	Cover	Button_entra
6/19/2020	11:18:48	P00	Button_sezRiti
6/20/2020	10:35:10	Cover	Button_entra
6/20/2020	10:35:13	Cover	Logo_Politecnico
6/20/2020	10:35:15	P15	Logo_Politecnico
6/20/2020	10:35:19	P15	Logo_Museo
6/20/2020	10:35:22	P15	Button_home
6/20/2020	10:35:24	Cover	Button_entra

Figure 5.17. An example of the log entries for calculating the time of interaction for a particular visitor. The highlighted area is an example of false entries.

After identifying the real interactions for each visitor who interacted with the application, it emerged that out of 4,532 visitors who visited the exhibition, a total of 639 visitors (14%) interacted with the application, and 77.5 hours of interaction was recorded. Subsequently, the minimum, maximum, and average time of interaction per person were calculated (Table 5.2).

Table 5.2: Analyses of the log data of PERVIVAL application

No. of days of data	73
Total time of interaction (Hours)	77:34:44
Average daily interaction (Hours)	1:03:46
No. Of visitors who interacted	639
Minimum time of interaction Per Person (Hours)	0:00:08
Maximum time of interaction Per Person (Hours)	0:56:13
Mean time of interaction Per Person (Hours)	0:07:17
Standard deviation of interaction Per Person (Hours)	0:07:07
More than 3 mins	65%
More than 5 mins	53%
More than 10 mins	26%
More than 15 mins	13%

Furthermore, the visitors were divided into four groups based on the total time (more than 3, 5, 10, and 15 minutes) of interaction per person. The percentage of these groups among the sample data is also reported in the following table. While most of the visitors took a synthetic overview of the application, the data clearly shows that the time proposed to explore the application in detail is not in accordance with the time that the visitor would spend on average with such an application. The actual time proposed before the visitors' evaluation was three minutes for a synthetic overview of the whole material (Level I) presented in the application or twenty to twenty-five minutes for complete navigation.

The log data was also analyzed to understand the visitors' navigation and general interests in different parts of the application and the most common types of interaction. A Sunburst Diagram that is usually used to visualize hierarchical data can also be used to identify user navigation sequences for various applications or websites [Rodden 2014]. Such a diagram is used here to visualize the interaction data of the visitors with the application (Figure 5.18).

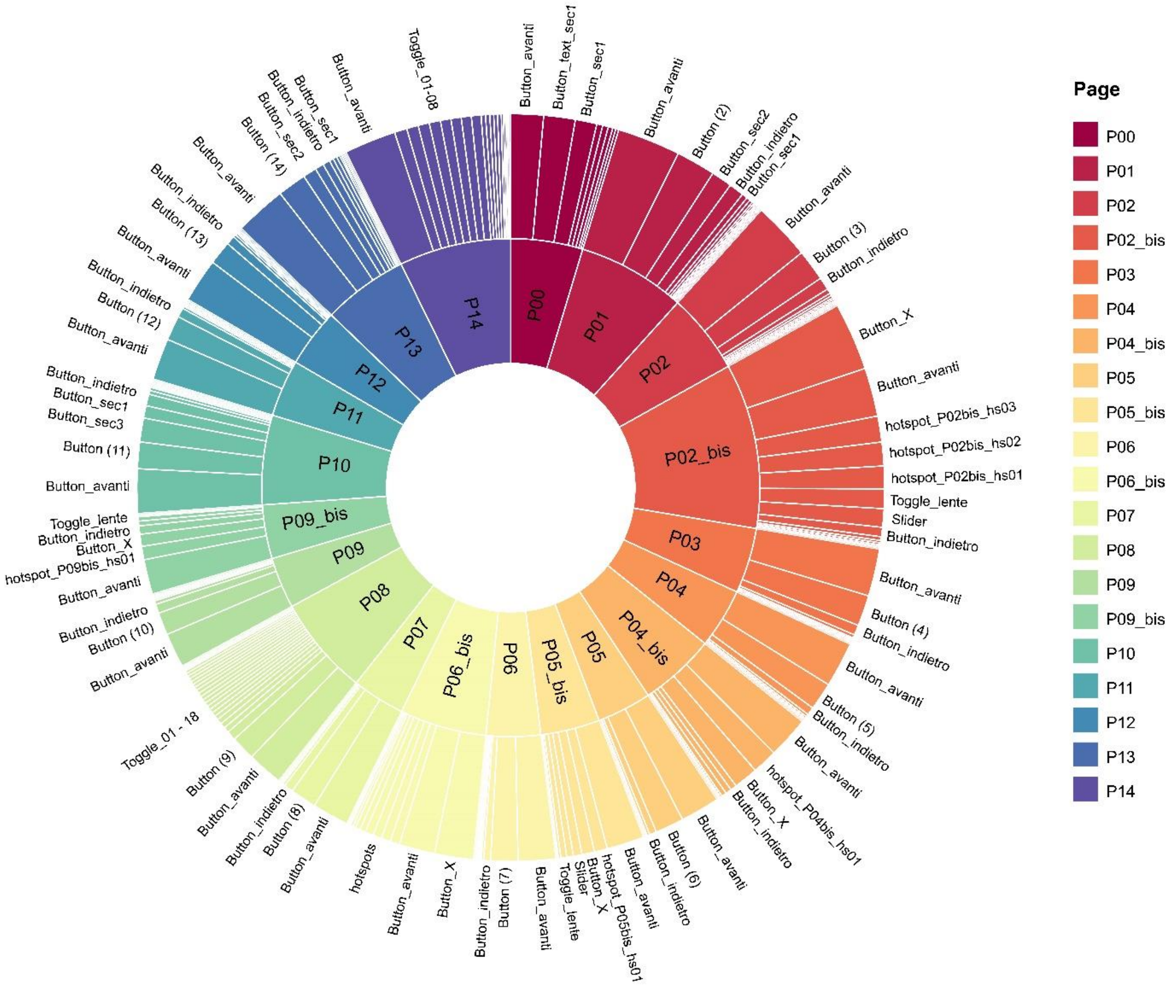


Figure 5.18. Sunburst diagram of visitor interaction at different pages of PERVIVAL application. The first hierarchical level represents the pages and buttons are at the second level. The width of each piece represents the number of interactions.

The visualization is based on the total number of interactions with a specific button on each page of the application within the recorded log data. The first hierarchical level represents the pages of the application where the interaction occurred and the second hierarchical lever represents different buttons on each page. The width of each segment represents the number of interactions where wider segments are those with more interactions and vice versa.

It can be seen from the visualization that most of the interactions occurred on the page "P02_bis". On this specific page, the visitors explored all the contents in detail which is represented by the width of several segments in the second hierarchical level representing buttons. Overall, the most used buttons were "button_forward" and "button_back". It implies that apart from the page "P02_bis", most of the visitors took a synthetic overview of the whole application without exploring each page in great detail. This observation also corresponds to the average time of interaction per person calculated i.e. 3-5 minutes for most of the visitors.

To confirm this observation and to demonstrate the most common paths of interaction, the log data was analyzed to draw a heat map of the sequence of interaction (Figure 5.19). A sequence of interactions was assigned to each identified visitor (a total of 639) in the log data. The first interaction of each visitor is represented by sequence no. 1, the second interaction is sequence no. 2, and so on. As each interaction started at the "cover" page and the only path from that page is to the page P00 (start page), the interactions at the "cover" page are represented by sequence no. 0. For ease of readability, only the first 30 sequences of interaction for each visitor are represented in the heatmap.

The sequence of interaction is represented on the x-axis in the heatmap while the y-axis represents pages of the application. The cells with more interactions are assigned a dark red color compared to the light red color for fewer interactions with most interactions (639) at the "cover" page with sequence no. 0.

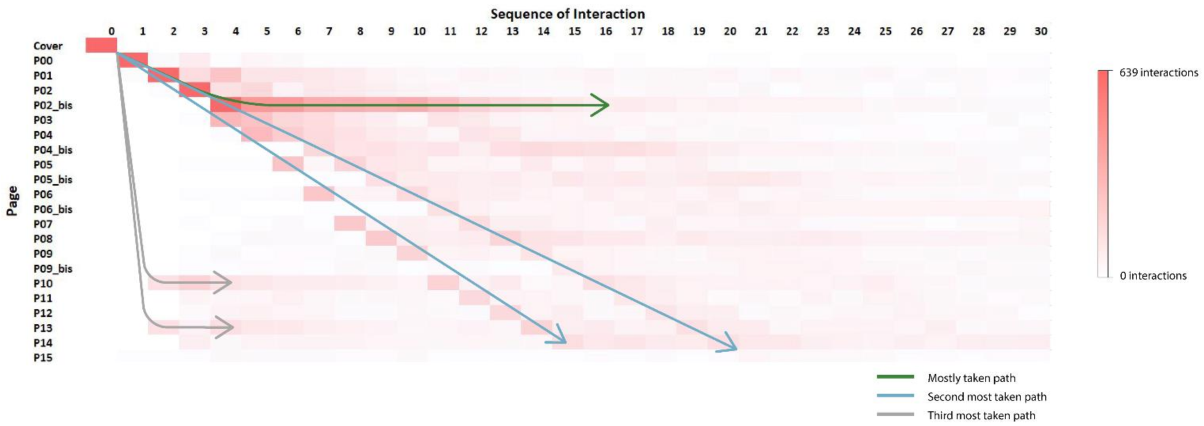


Figure 5.19. Heatmap of the sequence of the interaction of visitors with the PERVIVAL application. The most used paths are represented by arrows.

The arrow lines in three different colors show the most followed paths by the visitors. It can be seen that the most taken path by the visitors was the interactions and exploration in detail only until the page "P02_bis" (the path represented by the green arrow). The second most taken path was that of a synthetic overview of all the pages represented by blue arrows. Some of the visitors also took an alternative path of directly reaching the 2nd and 3rd page among the "level 1" pages selection from “P00”. These paths are represented by grey arrows in the heatmap. The most common paths taken by the visitors explain the way in which most visitors interacted with the application for an average time of interaction of 3-5 minutes (Table 5.2).

5.3.3 Personal meaning mapping (PMM)

To understand the visitors’ background and their learning from the digital experience, the PMM approach was used. The PERVIVAL application was designed to create interest and understanding among the visitors about the Egyptian funerary collections through digital reconstructions and narratives. Therefore, before interacting with the application, the participants were asked to share their knowledge about three learning keywords: *virtual archeology, Egyptian funerary rituals, and the mummification process*. After the interaction, the participants were asked to re-evaluate their answers before the interaction and if they wanted to change their thoughts about the same three words. This helped to determine whether the same words meant something else for the visitors after the interactive learning experience and what they took away from the experience. The comparison of the answers to the same questions before and after the visit was interesting to evaluate the effectiveness of digital interaction as an educational strategy.

Interacting with the application significantly changed the meaning of the three keywords among the visitors. They became more familiar with the subject topic and there was a substantial change in their perception of the word “digital” in the context of archeology. Most of the participants changed their answers after the visit from hardly knowing anything to the whole explanation of the phenomenon, or naming objects to explain the process. In fact, only 15% of the participants did not significantly change their answers after the interaction i.e. the expert visitors who were already well aware of the subject or the visitors who did not spend enough time in exploring the application (verified from the log).

Virtual archeology and its applications were understood better by the visitors after their interaction with the application. Before the interaction, most visitors related the virtual archelogy to mere 3D models. After the visit, virtual archeology applications were considered a shift from traditional passive museum learning to an active form of learning. The post-visit responses of the participants revealed that experiencing the application had changed their view of virtual archeology from the mere use of 3D digitization to “modern”, “educational”, “futuristic”, “virtual interaction” and “a simulation of the past”. It was seen as an interesting way to understand, visualize, and teach archeological artifacts' history in great detail. The importance of different types of 3D scanning and survey for documenting of objects and reconstruction of archeological finds was also mentioned several times.

Similarly, after the interaction, the understanding of Egyptian funerary rituals and the mummification process improved significantly among the visitors. Specifically, the inexpert visitors, who had little to no pre-knowledge of the subject, were able to explain the Egyptian rituals and mummification process in great detail in post-interview PMM. For example, one visitor in pre-PMM considered Egyptian funerary rituals as mysterious and complex. In post-PMM, he wrote: “I learned that this ritual was done because the Egyptians thought that preserving the body in this way allowed the soul of the deceased to continue living in the other world and also in the world of the living. In addition, through various personal objects and the mummification of the body, they believed that the soul would have a way to return to its body to rejoin after its wandering. I do not know exactly the steps but I think they removed the organs and kept them in different types of jars and containers". Another participant in pre-PMM answered "not sure" about the mummification process. In post-PMM he added, "now I know that the brain and the 4 main organs (lungs, liver, intestines, and stomach) were removed from the dead body. These organs were stored in small vases that were also buried with the dead. The heart stayed in place. The body was covered with salt/resin for about 40 days, before getting actually into the sarcophagus". Such learnings from the interactive experience also directly corresponded to the individual log information. In the above-mentioned examples, the visitor who explained Egyptian funerary rituals in detail spent 15 minutes interacting with the application. Out of the total time, he spent 10 minutes in section 1 of the application which is about the ritual related to "preserving the bodies". Specifically, he stopped for 3.5 minutes and tapped all the buttons on at the pages "P07" and "P08". Through animations and toggle buttons, these pages provide information about the canopic vases and the amulets that lay between the bandages of the mummy. Similarly, in the second example, the visitor spent 23 minutes interacting with the application, which was enough also to read the text information. The specific text that he reported in the post-PMM related to the mummification process and canopic vases was presented on pages "P02" and "P07" where he spent 4.5 minutes and interacted with the 3D models and reconstructions of the mummy for 4 minutes on page "P02_bis".

5.3.4 Questionnaire and interviews

The participants were also asked to fill in a questionnaire at the end of the visit. Out of 50 visitors of the exhibition who gave their consent to participate in the research 52% were female and 48% were male. While 29 visitors participated in this research alone, 21 visitors were in a group of at least two persons (friends, family, or partners). The age of participants ranged from 20 years to 62 years with most of them less than 35 years old (62%). As the application under study was monolingual, the vast majority of participants were Italian (74% of the participants). All the participants could understand the Italian language except three who were accompanied by a translator. Therefore, the questionnaire and interviews were conducted in the Italian language.

To understand the background of the participants, they were presented with five closed questions, with a range of 1 to 5, 1 containing the least weight and 5 containing the most weight. The overview of the responses provided in Table 5.3 shows that most of the participants were frequent visitors of museums in general and archeological museums specifically.

Table 5.3. Background of the research participants.

n=50 52% female; 48% male	Min value	Max value	Mean	Standard deviation
Frequency of visiting museums	2	5	3.54	0.98
Frequency of visiting archeological museum	1	5	3.42	1.13
Familiarity with Egyptian archeology	1	5	2.84	1.03
Familiarity with digital archeology	1	5	2.64	1.13
Ease at answering question	1	5	4.62	0.77

Even though there were some experts on Egyptian archeology and digital applications for archeology among the participants, most of them were very less familiar/unfamiliar with the subject and type of application under study. Nevertheless, most of the participants felt comfortable answering the questions.

As anticipated, half of the participants in this research did not feel comfortable answering the questions verbally. Therefore, the interview questions were also provided in form of the second and third parts of the questionnaire with 2 closed and 3 open questions respectively to understand the visitors' opinions and assessments about different aspects of interaction with the application.

The two closed questions in the second part were presented as multiple-choice checkboxes to understand the most effective aspects of visitor interactive experience with the application when they were alone or in a group. In these questions, the selection of multiple options was allowed. The overview of the responses in Table 5.4 demonstrates that while alone the participants appreciated the learning aspects and interactivity through 3D animations. As was later expressed during the interviews and open-ended questions, the results of closed questions also clearly show that the experience with the application could not be easily personalized for every type of visitor, and improvements in terms of interface and affordance could be made. On the other hand, when asked about the interaction with the application in a group, most of the participants found it useful for group engagement and fostering conversations.

Table 5.4. The effectiveness of different aspects of the digital application on the basis of research participants' voting.

When alone		
	No. of participants	% of total
Learning aspects	30	60%
Interactivity	29	58%
Personalization	17	34%
3D animations	26	52%
Look and feel	13	26%

When in Group		
	No. of participants	% of total
Group engagement	26	52%
Group interaction	26	52%
Collective learning	21	42%
Fostering conversations	25	50%

The third part of the questionnaire consisted of three open questions inviting the participants to describe merits, demerits, and suggestions about their experience.

Most of the participants found the application synthetic, simple, and rich in information for learning aspects. In terms of visual aspects the interactive 3D graphics, animations, different layers of details, high-quality images, and informative text were valued among the visitors. The participants were enthusiastic to see the 3D reconstructions. In particular, the expert visitors verified the validity of the digital reconstructions to reconstruct different situations and render the details that can't be seen in the physical objects. The interactive nature of the experience was appreciated as the visitors could choose their own pace to personalize navigation and selection for exploring the whole collection or parts of it. For the visitors who were experiencing a digital application for archeology in a museum for the first time, it was an innovative way for museum learning, reconstruction of the past, and understanding of history.

On the other hand, the participants found the pace of the animations slower than what they would expect. Exploration of an object in detail was only possible after the animations finished and it was not possible to re-launch the animations from a certain point during the course of animations. Similarly, though the long text narratives were appreciated by the expert visitors, the inexperienced visitors found them distracting and confusing. They instead suggested adding links that could open the text information on a separate page or even connect them to the internet for further exploration. The 3D animations and interactive tools were preferred by inexpert visitors and they recommended creating additional elements of involvement such as audio narratives, sounds, and customized creation tools.

For adults, it was easy to navigate and understand, but all the participants with children asserted that the interface should be made simpler to understand for children and teenagers. It was less intuitive for non-expert users to navigate through different levels. For example, most of the visitors could not understand that they could switch through different sections, therefore they were forced to follow the predefined path. They suggested improving the affordance of the tools and animated tooltips to guide them through the navigation.

Sometimes it was difficult to associate application contents with the physical objects. The most discussed reason was the position of the screen with respect to the physical objects, which made it difficult for visitors to look at the objects while using the application. For this reason, it was suggested to change the immobile experience into an itinerant experience by using multiple screens positioned in proximity of each object or by the introduction of augmented reality, which could make it truly immersive and engaging, passing from a passive to an active form of media.

5.3.5 Evaluation of Experience

The evaluation of the visitor experience presented here (Figure 5.20) is grounded in quantitative and qualitative data collected from the visitors who interacted with the PERVIVAL application. It could provide useful bases for designers and domain experts for designing interactive digital learning applications through complex museum collections. The user experience was evaluated based on the analysis of visitors' navigation through interaction logging, their satisfaction with the experience, and most repeated improvements suggested during the interviews. Such evaluations were grouped into three layers:

- The content as the starting point of interaction and generation of narratives to connect tangible and intangible components of the collection
- The design of experience in terms of visual and learning aspects
- Implementation of user experience solutions

The first two layers are interconnected, which means that the design of experience is driven by the type of content available and the type of content is driven by the requirements of experience design.

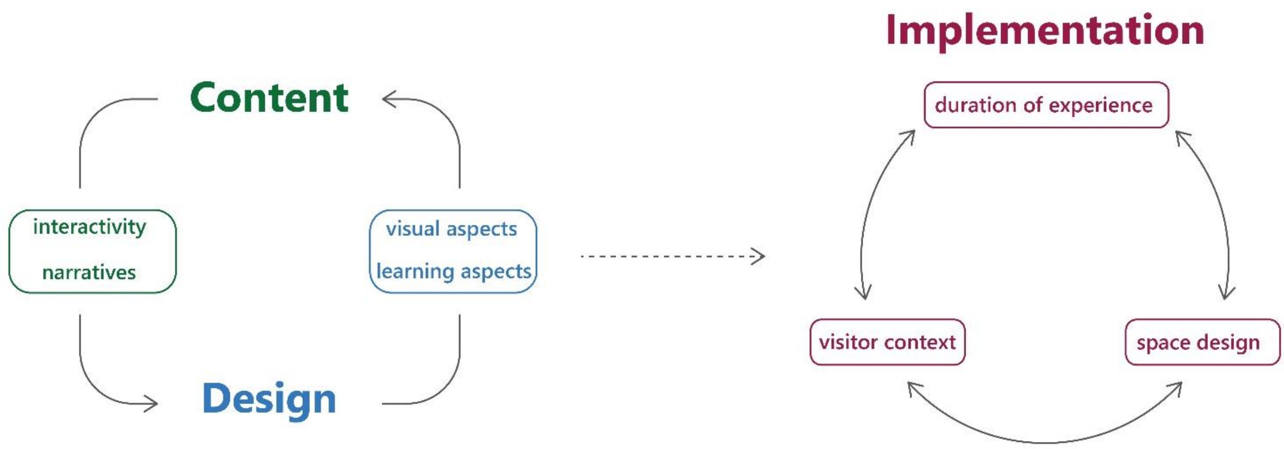


Figure 5.20. Evaluation of visitor experience based on visitors' interaction with PERVIVAL application.

Content

The evaluation of the PERVIVAL application presented in previous sections revealed that adding 3D interactions as a part of the experience while digitally presenting the museum collections is an effective tool for museum education and awareness, especially for inexperienced visitors. 3D interactions can trigger visitors' interest to learn about the history and context of the museum collections. Such information can be delivered through different layers of narratives connecting tangible and intangible components of heritage in chronological and geographical order through digitized artifacts and virtual reconstructions. The analysis of the log also confirms this observation as most of the visitors spent more time on the pages with 3D interactions and animations as compared to the rest of the pages of the application (Figure 5.18).

While delivering the interactive digital narratives for museum education proved to be effective, the visitors' data also revealed the importance of carefully evaluating some aspects of the content delivery before designing the experience. These aspects include: (i) the degree of interaction with 3D content, (ii) the pace of content delivery, and (iii) selecting carefully the digital items among texts, images, animations, 3D models, and sounds.

The interactivity with 3D models that proved to be the most important factor at the layer of content delivery, should allow visitors to fully interact at all levels with the digitized content. The users of the PERVIVAL application who were interviewed after their experience noticed a lack in the degree of interaction with 3D models and suggested improvements. During their interaction, locating any 3D model on the touch screen, they intuitively tried to turn and rotate, zoom in and zoom out the models, as someone would do on a cellphone by touching any part of the screen. But in the case of the actual application, the interactivity with 3D models was limited to rotation through a slider and zooming through a magnifying glass.

The pace at which the content is delivered is also important and must be managed at the layer of content delivery. Creating narratives through interaction to interlink the cultural stories is an efficient way to engage the audiences, but the length of individual components of the experience must be limited to a timeframe that does not become tedious for visitors to keep concentrated on the content. Several interviewed visitors found the animations in the PERVIVAL application to be sometimes slow and other times distracting because of the text which appeared at intervals. This observation was not common among visitors, therefor the comments related to the pace of content delivery were analyzed in the user context. Such analyses revealed that it mostly depends on the context of individuals i.e. previous knowledge of the topic, reading habits, etc. Foreseeing this issue, several glossary buttons were already added to the application. It can be further improved by allowing the users to personalize their own pace and to add hyperlinks to the internet pages for the visitors who want to explore further.

The pace of content delivery is also related to the decision of selecting the right digital items to present. The digital items presented in the PERVIVAL application included texts, images, animations, 3D digitized objects, and 3D reconstructions. While most of the visitors found it interesting to interact with 3D models (evident from the log analyses), excessive text and speed of animations were sometimes criticized. It was suggested to reduce the repetitive text, add a sound dimension for storytelling wherever possible, and to add personalization features for different users to choose their own content. Visitors found some digital items to be abundant for example 3D model of the sarcophagus was not needed as there was a physical counterpart near the screen. The model of the sarcophagus could have been useful for explaining the process of digitization, but there should be a balance between explaining the process and telling a story.

Design

After carefully selecting the content delivery methods the second step is to design the experience. Two main aspects of experience design emerged from the data collected from the users of the PERVIVAL application: (a) the visual aspects and (b) the learning aspects.

In terms of visual aspects, the affordance of any digital application is of utmost importance. The tools provided in the application should be intuitive for the visitors to understand the purpose and functionality without any guide. In the case of the PERVIAL application, it was observed that visitors sometimes found it difficult to find a piece of certain information and to interact with certain interactive tools such as hotspots and toggle buttons for in-depth exploration of information or sliders and magnifying glasses for interactive models. Furthermore, the application allowed access to the content via direct icon selection or through the predefined path. By intuition, the latter path was mostly taken by the visitors as it is highlighted in the analyses of the log for the visitors' path of interaction (Figure 5.19). It is evident that most of the visitors did not understand the explorative nature of the content and thus followed the predefined sequential paths. It was also the point of discussion during the interviews with several participants. A balanced solution can be found by creating a generative experience i.e. the possibility to jump between the information for expert or semi-expert visitors but also sequential for inexpert visitors who would usually need to read everything from the beginning to the end. The same is true in the case of animations. The users must not be imposed to wait for the animations to end to choose what they want to explore. In a similar way, the length of text could be alright for the people who want to read, but it should not be imposed in a way that the user must read all the text before he could go to the specific page of his interest.

The Learning outcomes analyzed through PMM and reported in section 5.3.3, also support the hypothesis of allowing a more generative and interactive experience specifically with 3D digitized and reconstructed objects. Most of the analyzed learning outcomes were based on the visitors' interaction on the pages of application with 3D objects and animations instead of the pages with long text descriptions.

Implementation

The user data suggests three evaluation components to implement any digital experience inside the physical space of a museum exhibition: (i) duration of experience; (ii) user context and (iii) space design.

The first component of implementation is to find a balance between the total time of user interaction with the digital application and effectively transmitting the learning content. The time proposed for complete navigation to read all content and interact with each artifact presented in the PERVIVAL application was 20 to 25 minutes. The log data of user interaction clearly showed the proposed time to be disproportionate compared to the time that the visitors spent on interacting with the application i.e. 7 minutes on average per person. Even though some visitors spent more than 15 minutes interacting with the application, most of the visitors stayed for only 3 minutes i.e. the time proposed for a synthetic overview of the presented contents. The duration component of the application was prominent during interviews with the visitors who found the long duration of the digital experience to be "tiresome". Furthermore, the researchers also observed the lengthy duration of visitors' interaction with the application to be problematic as there was often a queue of visitors to wait for their turn when an individual interaction lasted for more than 10 minutes. Therefore, the best solution is to divide the complex unique experience into an iterative experience distributed in space by using multiple screens in different locations around the museum collections. This certainly depends on the available budget and spaces to install such applications in museum exhibitions. A balance could be found by installing a general introductory screen with the synthetic overview of content at the entrance of the exhibition and another screen near the museum collection for in-depth learning of contents. In such a manner the visitors could personalize their experience at the entrance and select only the information of their interest on the secondary screen, thus avoiding the repetition of information and optimizing the overall duration of the experience.

Secondly, exhibition spaces interfere with the experience by creating a relationship between the visitor and the displayed contents. For temporary exhibitions, in particular, the setting of the exhibition space is an important component of the experience implementation layer. Space design is an important factor in the case of a digital application aiming at transferring knowledge through narratives and visitors' engagement in an exhibition space. For example, the data from interviewing users of the PERVIVAL application shows that the position of the digital screen with respect to the physical objects was not convenient for the visitors (Figure 5.15a). The digital screen was placed as opposed to the physical objects, thus the visitors found it troublesome to connect the digital content with the actual objects. Such difficulties were also observed by the researchers during the visitors' interaction with the application. Furthermore, different unrelated objects near the digital screen were considered "distracting" and "unpleasant" by the visitors. A solution is to introduce a mobile application with similar content, which can be downloaded by the visitors to move around the exhibition space in context to the real objects. Nonetheless, the digital screen is suitable for visitors who can not download the application on their mobile phones. Therefore, depending on the budget, a dual solution (application on both the digital screen and on a mobile device) could be the best solution.

The subjective nature and context-dependency in the field of user experience are widely accepted [Hassenzahl et al. 2010][Hassenzahl and Tractinsky 2006b]. It has also been shown that user experience is something personal. A group can experience together, but the experience we are investigating is still inside each individual of that group [Law et al. 2009]. Nevertheless, It is crucial to study the general context of the visit of a majority of the visitors of a specific exhibition before implementing a designed experience. This notion also emerged from the user data evaluation of the PERVIVAL application. For example, 30% of the exhibition visitors were accompanied by teenagers and adolescents, while the digital application interface and content were designed for an adult audience. Such disconnection between the context of visit and design of experience was mentioned several times during the interviews with the research participants accompanying children and the participants engaged with the education sector.

6. DEPICTION OF EVALUATED DATA: THE 3D-CULTEX FRAMEWORK

Lessons learned from the literature, analyses of the user data collected through mixed methods research, and best practices adopted in the presented case studies in previous chapters, are being represented in form of a framework in this chapter. Though various models and frameworks have been presented in the past as tools for designing experiences with different types of technologies, the framework presented here is a first attempt to develop a tool to evaluate the experience of 3D interaction and generation of the required quality of 3D models of CH assets in accordance to the requirement of the experience. As already stated in the introduction, the presented framework aims to provide useful guidelines and criteria for project developers, researchers, and cultural heritage institutions in order to develop enhanced cultural experiences through 3D digitization projects.

For a better understanding of stated guidelines and evaluation criteria, the roles of different stakeholders of 3D cultural experiences, and the beneficiaries of the presented framework, this chapter delineates different aspects of the framework and provides directions on how to navigate through it. The first section is an overview of the framework resulting from data collected throughout this research. It defines two main layers of the framework, sections of each layer, and the associated stakeholder (with who and for whom) with each layer of guidelines and evaluation criteria. An in-depth exploration of each layer of the framework separately through navigation matrices is provided in this section. It also illustrates how the framework could be applied in different scenarios. The second section supports the applicability of the framework by applying it to specific case studies.

6.1 The 3D cultural experience framework (3D-CultEx framework)

The evaluations of interviews from interdisciplinary researchers, combined with the guidelines from the literature review, were used as a starting point to create a theoretical framework. The preliminary framework was then enhanced and validated by grounding it into the data collected from the stakeholders through various activities explained in previous chapters. The resulting 3D cultural experience framework (3D-CultEx framework) is presented in Figure 6.1.

The main motivation of this representation is to create a tool that can assist in understanding the impact of smart usage and the quality of 3D digitization in developing experiences by engaging the pre-defined stakeholders at different stages of 3D content creation and usage. The framework is being visualized as a wheel with the 3D cultural experience at its core, while the design and creation of 3D content are represented by two layers around the core. The two layers around the core serve as (i) evaluation criteria of cultural experience by using the 3D digitized content for different purposes and (ii) guidelines for improving the quality of 3D digitized CH for the specific experience required. The stakeholders (professionals and end-users) of the research are presented in the outer ring of each layer based on their specific needs and role at different stages of cultural experiences development through 3D digitized CH. In essence, the 3D-CultEx framework can be understood by starting from the core of 3D digital experience towards the first layer of evaluating the requirements of experience and finally producing quality 3D contents from the second layer for the specific experience.

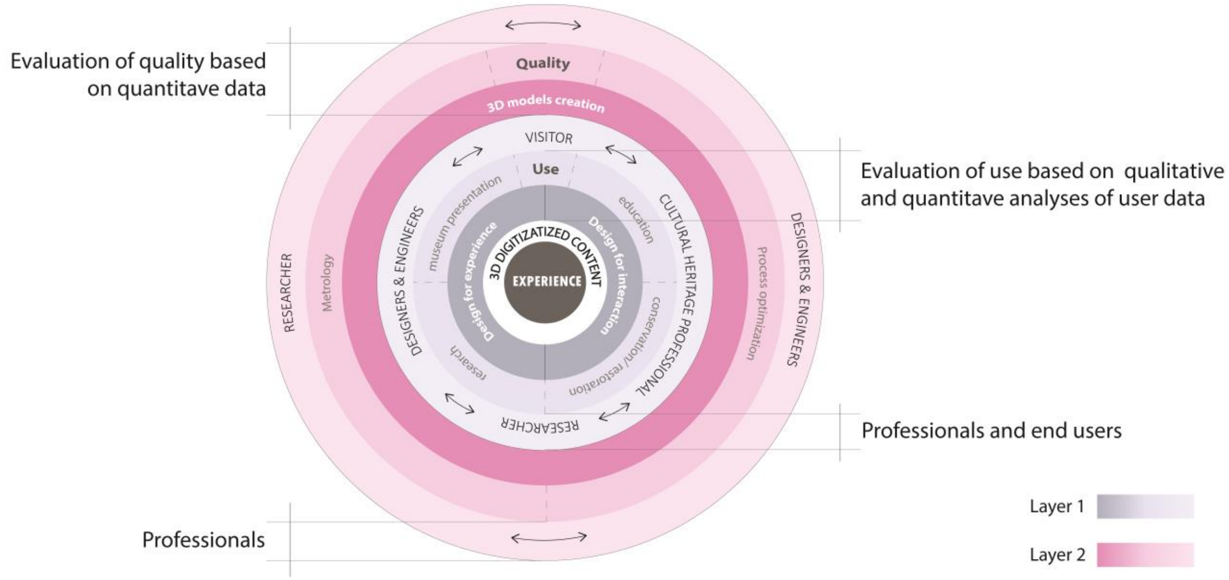


Figure 6.1. The 3D-CultEx framework representing content creation and usage by involving the stakeholders for an enhanced cultural experience with 3D digitization.

The experience through 3D technology is at the core to represent the ultimate objective of different uses represented in the first layer. The first layer around the core corresponds to the evaluation criteria for the main uses of 3D digitized CH i.e. education, research, conservation/restoration, and museum presentation. It evaluates different scenarios to assess the effectiveness of experiences that can be reached from 3D models. This layer has two sections to evaluate the design of experience and the design of interaction with the 3D digitization of CH. The second layer represents the quality of reality-based 3D models of CH assets. Based on the requirements and criteria of the first layer, the second layer provides guidelines for creating high-quality experience appropriate 3D models. The framework can be read by starting from the core of experience to the layer of use by evaluating the experience and interaction and finally to the second layer for producing high quality and detailed 3D models suitable for the requirements of experience.

A brief description of the different features of the framework is reported in the following subsections.

6.1.1 The stakeholders

Digital heritage and digital humanities require knowledge and expertise in both engineering and humanities. CH assets are the topic of research in both areas of study. Digital heritage deals with the questions related to the digitization of cultural, scientific, educational, and administrative resources. Digital humanities, on the other hand, focus on the application of digital technologies to support studies in the humanities, tangible and intangible aspects of cultural heritage for preservation, education, and research. Both fields employ digital technologies often in cross-disciplinary settings, and they often use similar technologies. Despite commonalities, often there is only little overlap between related scholarly communities in terms of involved researchers and research associations [Münster 2019].

With the advent of digital heritage, the older ideology of conservation must now share its directing role with the newer ideology of collaboration [Hooper-Greenhill 2013]. Specifically, in the experience-centered projects, which this research is dealing with, the cooperation between museum staff, researchers, content curators, designers, and end-users should be recommended and promoted. New research must take a perspective turn both in concept generation and in creating technical perspectives. The future project development and implementation must include all the stakeholders (professionals and end-users) to ensure successful digital experiences.

Therefore, in the 3D-CultEx framework, the professionals and end-users (stakeholders of this research) are represented in a collaborative role from both fields of digital heritage and humanities. The stakeholders who participated in this research during the data collection phase are represented in the outer rings of each layer of the framework. As it was discussed in the introduction, the stakeholders could be divided into two groups based on their needs and roles in developing cultural experiences through 3D digitization.

The first group is composed of the professionals involved directly or indirectly in the cultural heritage field. It includes the researchers and scholars in all the areas of study of this research ranging from digital heritage, design for CH, museum studies, art history, and archeology. This group also includes project creators i.e. engineers and designers of 3D applications. The second group is composed of the end-users for whom the cultural experience through 3D digitization is intended. It includes museum professionals both in technical and administrative categories and museum visitors i.e. the users of 3D applications both inside and outside of the museum.

The group of professionals lies in the outer ring of the second layer of the framework as they are associated with the guidelines of the outer layer of quality. The guidelines for the quality of 3D content do not concern the group of end-users, therefore they are represented only in the usage layer of the framework alongside the professionals, who in any case must be involved in all the stages of 3D cultural experience development.

Researcher

To counter the criticism of the increasing speed of capital, technology, and daily life, Caraher developed the concept of "slow archeology" [Caraher 2016]. This term advocates the positive effects and efficiency of utilizing digital tools in archeology. A similar concept could be applied to CH research, museum education, and presentations as the advances in "digital heritage" are challenging the traditional approaches (slow museology). Digital heritage includes a range of approaches and topics involving researchers from multiple disciplines. Due to the inherent complexity of digital heritage, interdisciplinary researchers have to confront methodological challenges related to digital experience evaluation. To deal with the growing tension between digitization and "slow archaeology" and slow museology, the researchers together with the other stakeholder must assess the value of digital approaches for preserving, communicating, and interpreting the past as it relates to the present [Harrison 2019].

In the post-digital museum with ever more acceptance and adaptation of digitized content by museums for onsite and offsite visitor engagement, the digital heritage researchers have to explore more complex questions compared to the traditional museology. Researchers now have more complex problems related to immersive and augmented experiences. In any experience-oriented project, they have to work closely with their research participants to navigate ambiguous terrain, including the often unpredictable affective resonances that are the direct consequences of interaction [Galani and Kidd 2019].

Virtual heritage is a branch of digital heritage which is often based on the use of 3D digitized artifacts of CH. 3D digital heritage can be successfully utilized in digital archeology and digital museology for the purposes of conservation/restoration, museum presentation, education, and research. However, currently, 3D models of CH are rarely seen outside of conference presentations, one-off museum exhibitions, or digital reconstructions used in films and television programs [Champion and Rahaman 2019]. There is a growing need for researchers to better sustain 3D models of CH assets both as replicas of physical cultural heritage (related to the quality) and as tools for different uses for improving cultural experiences for the end-users of these models. Therefore, in the 3D-CultEx framework researchers are presented in both the layers of usage and the layer of quality.

Visitors

In the 21st century, museums have changed from being static units for storing artifacts to active learning environments. It means that there is a need to connect with the audiences in new ways. Alongside researching about the past, the museums are also looking into new ideas and approaches to research their visitors and new audiences. Such a shift in the focus has created new challenges to create a relationship between the preservation of objects and their use in education and museum presentation [Hooper-Greenhill 2013]. On the other hand, in museum research, the digitization of CH has started to become the new norm. Consequently, the effects of the introduction of digital media on visitor experience have been largely studied.

Meanwhile, the adaptation of 3D media for CH has also become valuable in various contexts such as preservation/restoration, museum exhibitions, educational and recreational activities performed on-site, and as a way to promote CH assets through offsite and web experiences [Carmo and Cláudio 2013]. The wide availability and dissemination of 3D technology have changed the way how museums and CH institutions promote their assets. Specifically, there has been an increased emphasis on the co-creation of experiences with visitors. Latest advancements in augmented and virtual reality have further impacted the way people experience their museum visits. Research on augmented and virtual reality for CH has created opportunities for personalized museum experiences, which has resulted in the growth in museum visitors [Jung and tom Dieck 2017].

Therefore, if 3D digitization is to be successfully deployed in museum and heritage settings, understanding the personal, social and emotional context of visitors in the experience development process is of utmost importance. Hence, the visitors have been represented in the experience and interaction design layer. Including the visitor in the experience evaluation stage will inform museum professionals and researchers on how they can utilize 3D technology to enhance visitor experiences.

Cultural heritage professionals

Ever since the introduction of the term “postdigital museum” by Ross Parry [Parry 2013a], the impact of digitization and digital practices on the daily practices of CH professionals has become evident. To cope with this massive digital turn in museum practices, the “One by One” project looked into the existing digital skills and literacy of CH professionals developed and deployed in the UK museum sector and pointed out the required skills in “postdigital museums” [Barnes et al. 2018]. Grounded in case studies, non-participant observations, interviews, and focus groups, it was found that the digital practices of museum professionals are continuously improving and their digital skills are being professionalized and institutionalized. Furthermore, museums are exploring, learning, and demanding new digital skills. But, still museums assume that digital skills are related only to a specific set of technical competencies. Hence, currently, they are not systematically identifying and training museum professionals with new digital skills.

This approach of analyzing the digital skills of CH professionals in the context of museum practices somehow overlooked the actual perspective of the CH professionals on how museum digitization impacts their daily practices and experiences. The experiential, personal, and subjective perspective of the CH professionals in understanding the digital impact was not presented in the “One by One” project. Recently the “voice” of CH professionals in the digital turn of museums was included in the MUSETECH model. To demonstrate the significance of digitization for museums and their audiences, the MUSETECH model examines the perspective of CH professionals who are in charge of the daily design, deployment, operation, and continuous adjustment of technology for documentation, communication, management, and administrative purposes [Damala et al. 2019].

Similarly, during the past decade, the potential of 3D digitization has been increasingly recognized and adapted by CH professionals for opening up new possibilities for all the purposes defined in this research i.e. education, research, conservation/restoration, and museum presentation. Already in 2015, a survey demonstrated that there is a high interest in 3D imaging technologies across heritage institutions and the museum sector. The survey included CH professionals from both traditional roles (conservator, curator) and technical roles (digital documentation technicians) [Hess 2015]. Yet, currently, there is no comprehensive understanding among the CH professionals of what constitutes 3D digitization quality and how to evaluate their own 3D experience and the experiences they develop for the museum audiences through 3D digitization. Therefore, following the example of the MUSETECH model, which includes the CH professionals in digital technology design development and management, the CH professionals are represented in both the usage and quality layers of the 3D-CultEx framework.

Designers and engineers

The effective use of digitized CH assets contributes to the co-creation of value for both cultural heritage organizations and for visitors’ experience before, during, and after the visit [Jung and tom Dieck 2017]. Such co-creation of values does not only require relationships between the professionals and the visitors, but also multidisciplinary collaborations between the professionals. Through digital technologies, a multidisciplinary team can create virtual environments that are not only technically precise but also contain an emotional value for the users. Until now, the research in digitization has been focused more on technicalities (digitization, software automatization, and usability) rather than the hedonic aspects (such as emotions, senses, perception, and environmental atmosphere) [Pietroni et al. 2018]. But, the hedonic aspects of the experience have more profound effects on the value creation and meaning-making of experiences. Beyond perfecting the technicalities of virtual experiences, the complex emotional and personal phenomena must also be dealt with. Therefore, to create an authentic UX, a multidisciplinary collaboration between engineers and UX designers is required.

The frequent use of digital tools and advanced applications in the field of CH has increased the use of 3D models of CH assets. To develop the interactive systems for cultural experience based on such 3D models, UX designers and engineers/developers of digital applications should complement each other throughout the processes of design, development, and implementation for the benefit of both disciplines. An example of such collaborations was evaluated through a software tool CoDICE (COdesigning DIgital Cultural Encounters) [Díaz et al. 2015], developed under the framework of the meSch project [Petrelli et al. 2014]. The software served as a tool to support the developers and designers to allocate and distribute tasks and trace the outcomes of co-designed digital products for the cultural experience.

Following this example, the cross-disciplinary collaborations between designers and engineers are represented together with the other stakeholders in both layers of the 3D-CultEx framework.

6.1.2 The layer of uses of 3D in CH

The first layer of the framework provides evaluation criteria for 3D digitized content in terms of usage, for different purposes i.e. education, museum presentation, preservation, and research. Similar to the stakeholders, these uses are also clustered into two groups: professional uses (conservation/restoration/research) and end-user experiences (museum presentation/ education). All of the stakeholders of this research are represented in the outer ring of this layer. This part of the framework provides criteria for the design of experience and design of interaction with 3D models of CH objects.

Design for experience

The design of the experience is presented in the first section of layer 1 of the 3D-CultEx framework (Figure 6.2). It includes the evaluation of experience for the four main uses of 3D digitized CH artifacts. This section includes all the stakeholders of this research, which implies that designing the experience is a co-creation activity involving all the stakeholders (professionals and end-users).

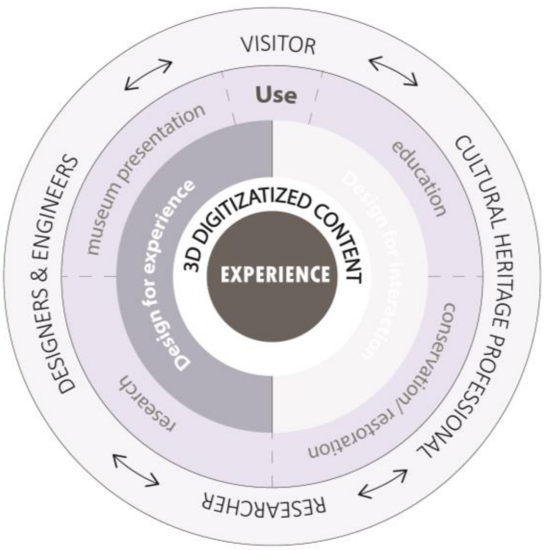


Figure 6.2. Design for the experience section of the Usage layer of the 3D-CultEx framework.

For a better understanding of functionality and applicability, different criteria of experience evaluation and the role of different stakeholders at each stage of experience development are presented in form of a matrix (Table 6.1). On the basis of analyses reported in chapter 5, three factors of experience evaluation (user context, context of use, and system design) are represented in the first row of this matrix. The second and the third row represent the stakeholders and evaluation criteria concerned with each factor respectively. The role of stakeholders at each step and related evaluation criteria are explained in the following subsections.

Table 6.1. Matrix for evaluation criteria of experience design and involvement of stakeholders at different stages of experience development.

			Context of use	**User context**		**System design**	
Stakeholders			• designers and engineers • CH professionals • researchers • museum visitors (for museum presentation an education only)	• CH professionals • researchers	• CH professionals • museum visitors	• designers and engineers	
				Direct involvement	Indirect involvement	Formal aspects	Technical aspects
Criteria for experience evaluation	**Museum presentation/ Education**	**From original artwork**	historical, political, spiritual, and artistic contexts original use intangible characteristics	professional needs tools expectations	motivations emotions background expectations	accessibility flexibility aesthetics affordance of applications hygiene (in museum exhibitions)	material, textures, and scale of physical replicas geometry and textures of digital replicas original feel
		Through 3D replica	high degree of interaction with 3D models annotated 3D models easy to augment digital models narratives				
	Research/ Conservation/ restoration	**From original artwork**	material feel and appearance metadata intangible characteristics				
		Through 3D replica	exact replicas of CH high-resolution 3D models precise 3D models easy to use applications easy to manipulate 3D models				

Context of use

The first factor is the context in which 3D models of CH are used as a starting point in any project or as research objects by scholars. The quality of 3D models can be selected by the researchers and project developers by evaluating the context in which they are used. In this research, four contexts in which 3D models can be used were pre-define. The four uses were further clustered into two groups i.e. end-user experiences (museum presentation/education) and professional uses (conservation/restoration/research). For each group of uses, there are different needs of the stakeholders and therefore specific quality and details of 3D models will be required. Hence, this factor can support the evaluation of the use of 3D models for the four contexts of use.

Stakeholders

At this step, the experience must be co-designed by involving all the stakeholders. Therefore, both professionals and end-users are involved here.

For two groups of uses, the evaluation of the experience is based on:

- the capability of 3D models to represent the important aspects of the original artwork
- the values that 3D models can add to the experience

Museum presentation/education

The first group of uses of 3D models is for museum presentation and education. In this case, the 3D models must present the historical, political, spiritual, and artistic context of the original artwork. The original context of use and intangible properties of the original CH assets are also important to consider for the digital experience for this group of uses. To add value to the digital experience for these uses, the 3D models are required to have a high degree of interaction, and annotations for narrative creation and must be easy to manipulate.

Conservation/restoration/research

The second group of uses of 3D models is conservation, restoration, and research. For creating a digital experience for these uses, the 3D models must present the material, feel, appearance, and intangible characteristics of the original artwork. The metadata of the objects is also important for these uses. The 3D models in this case must be exact replicas of the original artworks. It requires precise models with high-resolution texture and geometry. The 3D models for these uses must also be easy to manipulate and the subsequent applications must be easy to use.

User context

The second factor of experience design is the context of both professional users and end-users. This part provides some evaluation criteria for designing the experience and the eventual creation of a 3D digital experience on the basis of user context. The users of 3D models can be divided into two groups: the professional users who work directly with the physical work of art or heritage objects (e.g., restorers, researchers, art historians) and the end-users who do not directly interact with the physical artworks (e.g., museum visitors, educators in schools or museum education units). The experiences must be designed in the context of their needs and backgrounds.

Stakeholders

At this step, both professionals and end-users are involved in order to evaluate their needs and requirements. The designers and engineers being the system designers are excluded at this step.

Direct involvement

The professional needs and expectations of the expert users who work directly with the physical CH objects must be evaluated at this stage of designing the experience. For conservators, researchers, and art historians, exact replication of the artwork is essential to facilitate their existing practices. By using 3D replications of CH objects, the tools designed for the professionals must not be very different on the operational level compared to their traditional tools.

Indirect involvement

For designing the experience for end-users, it is important to examine their motivations, emotions, and background. For museum visitors, apart from the representation of reality, the 3D models must also present additional layers of functional and engaging narratives. The visitors' emotions or memories can be triggered by providing personalized information. For educators, the applications representing the 3D models must be self-explanatory to avoid confusion and the feeling of being overwhelmed, hence improving the efficacy of the learning process by saving time.

System Design

The third factor in designing experience is the design of the system, which in the context of this research implies the interaction of users with 3D models through digital applications in museums or in a research environment. For a successful system design for enhanced user experience, both technical and formal aspects of such applications must be evaluated.

Stakeholders

This step is related to the design and development of digital applications with 3D models, which do not involve the end-users. Therefore, only designers and engineers are involved in the phase of system design.

Formal aspects

The formal aspects of interaction design such as accessibility, flexibility, aesthetics, and hygiene must be dealt with at this step of designing the final applications with 3D models of CH.

Technical aspects

Depending on the type of application, the technical aspects of the digital/physical applications of 3D digitized CH assets must be evaluated. In the case of the final application being the physical reproduction of CH assets through 3D printing, the selection of materials, textures, and scale is important. For the efficiency of physical reproductions, the original feel is as important as the original look, which means the right selection of 3D printing material, texture, temperature, shape, and weight. Similarly in the case of digital applications, depending on the type of application, the geometry and textures of 3D models must be selected carefully. The applications must also be comprehensible for both the professional users (mostly unwilling to use new technology instead of traditional tools) and end-users (specifically those who are not used to 3D digital technology in daily life).

Design for interaction

The design of user interaction with the 3D models of CH assets is the second section of layer 1 of the 3D-CultEx framework (Figure 6.3). It evaluates the interaction for the four pre-defined uses of 3D digitized CH artifacts. Similar to the section on experience design, this section also includes all the stakeholders of this research. Thus, designing the interaction is also a co-creation activity involving all the stakeholders (professionals and end-users) of this research.

Figure 6.3. Design for interaction section of the Usage layer of the 3D-CultEx framework.

The three stages of designing the interaction between the users and 3D digitized CH assets and the role of different stakeholders at each stage are presented in the following matrix (Table 6.2). On the basis of analyses reported in chapter 5, three stages of interaction evaluation (content, development, and implementation) are represented in the first row of this matrix. The second and third rows represent the stakeholders and evaluation criteria concerned with each stage. The role of stakeholders at each stage and related evaluation criteria are explained in the following subsections.

Content selection

3D interactions are an effective tool not only as a part of the experience for education and awareness in digital museum presentations but also to facilitate the practices of CH professionals and researchers. Through 3D interactions, visitors can effectively learn about the history and context of CH assets, and CH professionals and researchers can perform their activities in a more effective way. The effectiveness of such 3D interactions depends on the different layers of narratives connecting tangible and intangible components of heritage, which can be delivered in thematic, chronological, historical, or geographical order through digitized artifacts and virtual reconstructions.

Stakeholders

Professionals and researchers with different expertise must be involved in the content selection process. All the stakeholders except the visitors are presented in the matrix at this stage of interaction design.

Tangible

The 3D models of CH must allow the visitors and professionals to fully interact at all levels with the tangible aspects of the artifacts. 3D models of a museum object, presented through digital systems or physical replicas, must allow people to feel and manipulate them by performing gestures or bodily movements.

Intangible

Presenting narratives through 3D interaction to interlink the cultural stories is an efficient way for the engagement of museum visitors. Furthermore, through annotated 3D models the professionals can make use of interdisciplinary information on one platform. However, at this stage of content delivery, the length of individual components must be limited to a timeframe that does not become tedious for visitors and confusing to keep concentration for the professionals. This is also related to the decision of selecting the right digital items to present among texts, images, animations, sounds, and 3D models.

Table 6.2. Matrix for evaluation criteria of designing interaction with 3D models of CH and involvement of stakeholders at different stages of designing interaction.

	Content selection		Interaction development			Implementation					
Stakeholders	• designers and engineers • CH professionals • researchers		• designers and engineers			• designers and engineers • CH professionals • researchers • museum visitors			• designers and engineers • CH professionals • researchers		
Criteria for experience evaluation	tangible	intangible	**Museum presentation/ Education**		**Research / Conservation / restoration**	**Museum presentation/ Education**			**Research / Conservation / restoration**		
			visual aspects	learning aspects	user needs and context	museum goals	Space design	duration of interaction	research/professional objectives	application	accessibility
	degree of interaction with 3D content	narratives selection of suitable digital items among texts images animations 3D models sounds	affordance of use creating generative experiences avoiding excessiveness of content	history of museum collections relationship between tangible and intangible components of collections contemporary and original stories and uses of museum objects narratives	shape and material analyses multiple layered models exact replicas history and context	accessibility of museum content to a wider audience museum education, visitor engagement, and involvement through virtual models enhancing existing practices through augmented models	develop a connection between digital and physical space enforcing emotional relationships between the visitor and displayed content minimum distractions in the space	the pace of content delivery a balance between physical and digital experience non-continuous digital experience long enough to transmit learning contents not too long to become tiresome	easy to study the tangible and intangible properties of CH objects storing and managing metadata added value to the existing research methods	appropriate for the type of CH objects and type of research	acquiring and operational cost availability complexity

Interaction development

The second stage of interaction design is the development of interaction between users and 3D models through digital applications. Similar to the experience design section, the uses of 3D digitized CH assets are clustered into two groups i.e. end-user experiences (museum presentation/education) and professional uses (conservation/restoration/research). The end-user interaction is being evaluated in terms of visual and learning aspects. The professional users' interaction is being evaluated in terms of user needs and context. The quality and features of 3D models for CH applications can be selected on the basis of this interaction evaluation.

Stakeholders

The stage of interaction development is concerned only with the development of digital applications with 3D models of CH objects. Therefore, only the designers and engineers are involved at this stage.

Museum presentation/education

For the first group of museum presentation and education, the visual and learning aspects of user interaction with digital applications must be evaluated.

In terms of visual aspects, the affordance of digital tools presenting the 3D models for museum presentation and education must be thoroughly designed. The interfaces of applications must be intuitive for the visitors and educators to understand the purpose and functionality of the tools without manuals or guides. Furthermore, the generative design of digital applications can be useful to create a balance between the explorative and sequential nature of content delivery of digital applications. Such generative experiences can provide the users with the possibility of both sequential exploration of content and skipping between the information whenever and wherever they want. Finally, wherever possible, excessive digital items and information must be avoided.

The visual aspects are also related to the learning outcomes of the digital experience. Creating a generative and interactive experience specifically with 3D digitized and reconstructed objects is an effective way of audience engagement for effective learning through digital applications. For learning through such digital applications, the 3D models in these applications must enable the users to learn about the history of museum collections by creating a relationship between tangible and intangible components of collections. Furthermore, the 3D models in these applications must also present the narratives to understand the original stories and contemporary interpretations of CH assets.

Conservation/restoration/research

For the second group of museum Conservation, restoration, and research, the capacity of digital applications to present accurate information through 3D models must be evaluated. The 3D models presented through such digital applications must present the exact replicas of CH assets for shape and material analyses. For making the process of analysis easier for the professionals, the digital applications must have the ability to present multilayered models. Furthermore, the digital applications must also allow annotations for presenting 3D models with history and context.

Implementation

The third stage of interaction design is the implementation of designed 3D interaction. The implementation stage is also divided into two groups of uses i.e. end-user experiences and professional uses. For each group of uses, the requirements of implementation are different, hence the implementation of interaction must be evaluated differently. The implementation of interaction for end-user is being evaluated in terms of museum goals, space design, and duration of the interaction. The implementation of interaction for professional users is being evaluated in terms of research objectives, type of application, and accessibility.

Stakeholders

At this stage, the requirements of interaction must be co-evaluated with all the stakeholders. Therefore, both professionals and end-users are represented at this stage.

Museum presentation/education

For this group of uses, the implementation of 3D interaction must be according to the museum's goals of education and promotion of CH assets.

Firstly, any 3D interaction implemented for the end-users must enhance the existing practices for achieving the museum goals of visitor engagement, visitor involvement, museum education, and making their content available to a wider audience.

Secondly, the space of exhibition around the digital experience also has an influence on the quality of the experience. For a successful implementation of interaction, the digital experience must create a strong relationship with displayed content in the surrounding physical space. The space around the digital experience must also enforce the emotional relationship between the visitor and displayed content with minimum distractions in the space.

Thirdly, while implementing digital interaction, a balance must be found between the duration of digital experience and effectively presenting the digital content and transmitting learning content. The length of digital experience must be long enough for reaching the learning and interpretation goals but not too long to become tiresome for the users.

Conservation/restoration/research

For this group of uses, the implementation of 3D interaction must be in accordance with the research/professional objectives, the field of application, and accessibility for researchers and professionals.

Firstly, The digital applications with 3D models of CH must help the professionals to study all the tangible and intangible properties of CH objects. This can be achieved by connecting the 3D models of CH objects with comprehensive metadata that is easy to manage and search. The data management and operativity of such digital applications are also related to how different professionals are traditionally trained in their respective fields. The digital applications should serve as an added value to the existing CH research and practices instead of completely transforming them.

Secondly, the appropriate application must be employed for the type of CH objects and research objectives. For example, a highly precise and detailed 3D model of a sculpture or a painting through an AR application can be excellent support for conservation/restoration purposes. The historical evidence of archeological objects and environments, which are traditionally studied by

2D images, can be examined better by adding three-dimensionality on a digital screen. Similarly, physical replicas of CH objects starting from precise 3D models can be used as a tool for research even if the researchers are physically apart from the actual CH site or object.

Finally, the digital applications should be easily accessible to the researchers and professionals in terms of availability, complexity acquiring, and operational cost.

6.1.3 The layer of quality of 3D models of CH

The second layer of the framework provides guidelines for obtaining the best quality and post-processed 3D models of CH assets for designing user experiences for pre-defined uses (education, research, conservation/restoration, and museum presentation). By using this layer of the framework, the professional users (researchers, designers, and engineers) can obtain the best quality and post-processing of 3D models of CH objects for any required experience. The stakeholders (professional users) of this layer are represented in the outer ring and the quality of 3D models in terms of process optimization and metrological challenges is represented in the inner ring (Figure 6.4).

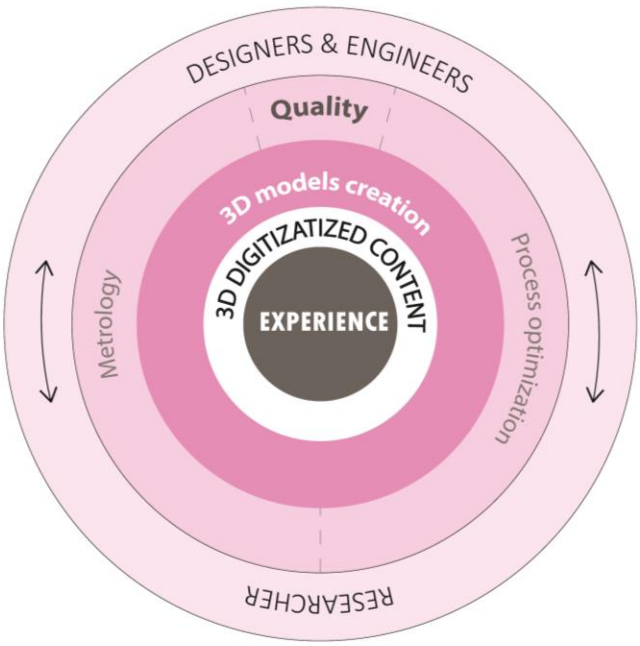


Figure 6.4. The layer of 3D quality of the 3D-CultEx framework.

For a better understanding of functionality and applicability, various guidelines on quality and post-processing of 3D models of CH objects at different steps are represented in form of a matrix (Table 6.3). As discussed in the introduction, these guidelines concern the 3D model creation and processing pipeline only through photogrammetry.

On the basis of laboratory tests and best practices in massive 3D digitization of CH objects reported in chapter 4, five steps of 3D model creation and optimization (assessment, setup, image capturing, 3D model creation, and post-processing) are represented in the first row of this matrix. The second row represents different factors affecting the quality and time of 3D model creation and processing at each step. The following rows provide some examples of creating high or low quality of 3D models with more time per process in the higher row. In each column, the red, orange, and yellow colors represent the difficulty and process time to achieve the best quality. The red areas require more time per process and high quality with respect to orange and yellow areas. The white area instead represents the technical choices to be made on the bases of the previous step. The total time of 3D model creation and processing is the sum of time per process at each step.

The five steps of 3D model creation with all the factors affecting the quality and time of model creation with several examples are reported in the following subsections. At each step, the decisions must be made to find a compromise between quality, total time spent for 3D model creation/processing, and cost of equipment.

Table 6.3. Matrix of guidelines for evaluating the quality of photogrammetric 3D models of CH. For each process, for better quality, more time per process is required in the higher rows than the lower rows.

Assessment					Setup			Image capturing		3D model creation			Post-processing	
			Working conditions								Processing			
Size of object	Complexity (surface/shape)	Lighting conditions	Placement of object	Permissions	Camera and lens	Attachments	Targets for scaling	Number of images[34] (overlap)	Image quality	Image balancing	Number of polygons	Quality of texture	Decimation	Annotation, metadata, and paradata
large > 8 m^3 examples • sculpture groups • big sculptures (more than life-size) • architectural scale	high examples • cavities, hidden details, and shadowy areas • small details (hands, feet, etc.) • shiny/dark objects • Small details on an architectural scale	low natural light examples • closed dark rooms • underground archeological remains • outdoor at night	difficult to reach examples • close to wall • at high places • inside the glass displays	limited examples • limited movement allowed • limited time allowed • minimum distance to maintain from an object • no drones • no scaffolding	Depending on finances, assessment of object and working conditions examples • for shooting the backside of a sculpture in the museum a) camera: Sony α6000 b) lens: Zeiss Touit 12mm f/2.8 c) attachment: HVL-RL1 LED ring light		many targets examples • medium-sized objects with comfortable to reach placement • large-sized objects with comfortable to reach placement	medium (optimal) range of design factor q= 4.7–6.2	high-quality images (low GSD)	High full brightness contrast and color adjustment in the RAW format from the camera	high > 4 million examples • medium-sized objects with high details • large-sized objects with medium details • large-sized objects with high details	High ≥ 16 megapixel examples • medium-sized objects with high details • large-sized objects with medium details • large-sized objects with high details	high < 1 million poly. examples of use • uploading on websites • real-time engines	Extensive examples of final use • educational applications • restoration/ preservation/ research
medium < 4 m^3 examples • life-size sculptures • medium-size sculptures • sarcophagus	medium examples • clothing details in sculptures • face details in sculptures • Small details in medium-size objects	medium natural light examples • museum galleries • indoors with windows	medium difficulty examples • no obstruction around objects but objects at high places • normal height of objects but obstructions around the object		• for shooting tall sculptures outdoors with enough space around and limited permission. a) camera: Sony α6000 b) lens: Zeiss Sonnar 24mm f/1.8 c) attachment: camera attached on a 6m monopod remotely controlled by a smartphone		a few targets examples • small-sized objects • medium-sized objects with difficult to reach placement • large-sized objects with difficult to reach placement	high range of design factor q > 9.3	medium quality images	medium adjustment of exposure, brightness, and contrast in the RAW format from the camera	medium < 4 million examples • small-sized objects with high details • large-sized objects with small details • medium-sized objects with medium details	medium = 8 megapixel examples • small-sized objects with high details • large-sized objects with small details • medium-sized objects with medium details	medium < 4 million poly. examples of use • rendering for videos • AR apps	
small < 1 m^3 examples • fragments • vases • busts	low examples • smooth surface • rich texture • bricked walls	high natural light examples • outdoors with daylight • indoors with studio lights	comfortable to reach examples • no obstruction around objects • low height objects	full • no restrictions from the authorities or administrators	• modeling of small Terrestrial finds, mural architectural structures and ornaments in outdoor lighting with full permission and enough space around the objects. a) camera: Canon 10D (6 Mpixel), Canon 20D (8Mpixel), Kodak DCS Pro (12Mpixel) b) lens: 24 mm, 20 mm, 50 mm c) attachment: none		no targets[35] example use of a laser scan for speeding up the scaling process architectural scale (simple measurements)	low range of design factor q < 3.8	low quality images (high GSD)	none direct use of photos from camera in .jpeg format	low < 1 million examples • small-sized objects with low details • small-sized objects with medium details • medium-sized objects with low details	low = 4 megapixel examples • small-sized objects with low details • small-sized objects with medium details • medium-sized objects with low details	none > 1 million poly. examples of use • digital archiving • digital restoration and monitoring of endangered CH • reconstruction of lost CH • archeological research	Limited examples of use • online museum websites • interactive museum exhibitions

Process duration ↑

Total time of 3D model production →

[34] For closed range photogrammetry on the basis of lab experiments [Guidi et al. 2020b].

[35] Scaling the photogrammetric model by using a single laser scan without using physical targets [Malik and Guidi 2018].

Assessment

The first step of 3D model creation through photogrammetry is the assessment of the object to be digitized and the conditions around it. This step is a literal observation to access the situation and permissions for digitizing a CH object. Therefore, the total time required for this step and the eventual effect of circumstances on the quality of the resulting 3D model does not depend on the experience or choices of the operator at this step. However, the quality and timing of 3D digitization can be optimized by carefully assessing the situation before starting the photogrammetric survey and making technical choices accordingly in the next step.

The sizes (small, medium, and large) and complexity (high, medium, and low) of CH objects categorized in Table 6.3 are based on the best practices that emerged from trial and error during the massive digitization of museum objects and archeological environments. While the assessment of lighting and working conditions are categorized from difficulty to easiness of common situations that a photogrammetric surveyor can face for digitizing CH assets.

Size of object

The first factor that a photogrammetric operator must analyze is the size of the object. To achieve a higher quality of 3D model from photogrammetry, generally, more time is required for the bigger-sized objects and vice versa. But the size of the object is related also to the shape and surface complexity of the objects, which means a bigger object will low surface complexity might be simpler to digitize than a small object with greater surface complexity. Objects such as the sculpture groups, more than life-size sculptures, and buildings, which were calculated to have an average volume of the bounding box of more than 8 m^3 are categorized as “large”. Other objects such as life-size sculptures, medium-size sculptures, and sarcophagus, which were calculated to have an average volume of the bounding box less than 4 m^3 are categorized as “medium”. Whereas the objects such as fragments of archeological objects, vases, and busts, which were calculated to have an average volume of the bounding box less than 1 m^3 are categorized as “small”.

Complexity (surface/shape)

The second factor to be evaluated at the step of assessment is the surface complexity in comparison to the size of the object. Some examples of details that can be considered highly complex are cavities, shadowy areas, hidden areas, small details such as the hands/feet of a sculpture, shiny/dark areas, and small details on an architectural scale. Features such as clothing/face details in sculptures or small details in medium-size objects are categorized as moderately complex. Other features such as smooth surfaces, richly textured surfaces, and bricked walls are categorized as simple in terms of complexity.

Lighting conditions

The availability of enough natural or artificial light suitable for photogrammetry is an important factor in the assessment step. Even though it is possible to achieve high-quality images in low lighting conditions with an appropriate setting and selection of equipment, generally such conditions result in low-quality images and more time in image capturing. The objects placed in closed dark rooms, underground archeological remains, and outdoor images captured at night can be categorized as “low lighting conditions”. The objects placed in museum galleries or other places indoors with windows are categorized as "medium lighting conditions". Some examples of high lighting conditions are an outdoor image captured in daylight and indoors shooting with professional studio lights.

Working conditions

Before setting up the image capturing equipment, the working conditions must be analyzed. The most important working conditions are the placement of objects with respect to surrounding space and the permissions from the authorities to work in the ambient of a museum or a CH site. The difficult working conditions can reduce the quality of 3D digitization and can increase the total time of 3D model creation. However, the generation of high-quality 3D models in such conditions is still possible by spending more time in subsequent steps and careful setup of equipment.

Placement of object

It often occurs while digitizing the CH objects that they are located in places that are not suitable for capturing all the details and it is often impossible to move them either because of lack of permission from authorities or unaffordable cost. Some examples of conditions that can be categorized as difficult include objects placed close to walls or at high places and objects placed inside the glass displays. The objects placed at height with no obstructions around and objects of normal height surrounded by obstructions are categorized as objects of medium difficulty. The objects with low height and objects with no obstruction around them are categorized as low-difficulty objects.

Permissions

The permission to work freely or with restrictions also affects the efficiency of the 3D digitization process. Some examples of difficult conditions in terms of permissions are restricted movement allowed around the objects, the limited time allowed, minimum distance to maintain from the object, and no drones or scaffolding allowed in the area around the object. The working conditions can be categorized as comfortable when there are no restrictions from the authorities/administrators of museums or CH sites.

Setup

The second step of the photogrammetric 3D model creation pipeline is the selection of the right equipment and setting up the space for photo capturing. The setup of equipment and space must be in accordance with the previous step of assessment of objects and working conditions. The choices made at this step can optimize the process by generating high-quality 3D models in less time.

Camera lens and attachments

The first factor in the setup step is the selection of photographic equipment. Such selection must be based on the careful assessment of the object and working condition. It also depends on the finances available for digitization. High quality of the 3D model in less time and at low cost can be achieved at this step when the working conditions are favorable and the object to be digitized is less complex. However, for more complex objects and difficult working conditions, high quality can still be achieved by making a careful selection of equipment. The examples of equipment selection shown in Table 6.3 are some of the choices made by carefully assessing the objects and surroundings in the previous projects.

Targets for scaling

A precise 3D model can be obtained from photogrammetry by placing homogeneously the physical targets for scaling around the object to be digitized. The distance between the physical targets in space is then measured before capturing the photos. These targets can then be detected by photogrammetry software and the 3D model of the object can be accurately scaled by associating the same distance values taken in the physical space before capturing the model. However, sometimes the placement of the object in a difficult position makes it complicated to place many targets around it. Furthermore, the placement of targets around the object and measuring the distance between them is a lengthy process that increases the overall time of 3D digitization. Therefore, a method to scale the digital 3D models through a laser scan without placing the physical targets around the objects was proposed in a previous publication [Malik and Guidi 2018]. Some examples of museum objects and the places where it is possible to place many targets are medium-sized objects with comfortable to reach placement and large-sized objects with comfortable to reach placement. Whereas a few targets can still be placed around small-sized objects, medium-sized objects with difficult to reach placement, and large-sized objects with difficult to reach placement.

Image capturing

After assessing the object and setting up the equipment and space accordingly, the third step in 3D digitization through photogrammetry is image capturing. At this step, the operator must define the total number of images of the object i.e. the overlap between consecutive images, and the quality of images i.e. ground sampling distance (GSD) of the images. Both of these factors determine the quality of 3D models generated from photogrammetry.

Number of images (overlap)

The overlap between consecutive images is an important factor in photogrammetry in achieving high-quality 3D models. The higher overlap between the consecutive photogrammetric images usually produces denser 3D clouds in the step of 3D model creation. However, if the overlap is very high the 3D clouds can have much higher unwanted noise, which results in low-quality 3D models. Under the scope of this research, the optimal overlap between consecutive images in a convergent shooting for close-range photogrammetry was investigated through test objects in the laboratory [Guidi et al. 2020b]. The optimal lateral displacement was represented in terms of distance/baseline ratio or "design factor" (q). The results of these tests were used to quantitatively explore the influence of "q" over the quality of a 3D dense cloud generated by photogrammetry. In the experimental conditions described in chapter 4, the results showed the dense clouds generated photogrammetrically from all test objects produced lower RMS error for "q" in the range 4.7–6.2. Whereas, high RMS errors were observed for the value of "q" higher than 9.3 or less than 3.8.

Image quality

The resolution of the images suitable for the photogrammetric process can be determined by carefully selecting the "Ground Sampling Distance" (GSD). GSD is a term that is used originally in aerial photogrammetry. It can be determined by the distance between the camera and the surface of an object, the size of the pixel over the photographic sensor, and the focal length of the lens used for taking the images. Therefore, apart from the equipment selection at the previous step, the distance of the camera from the object also affects the final quality of the images. The lower GSD results in higher quality images and vice versa.

3D model creation

The captured images are processed for creating the 3D photogrammetric model at this step. This step includes the correction of taken images if required, and the creation of 3D geometry and 3D texture. The image correction depends on the lighting and working conditions in the first step and on the correctness of captured images. While the quality of geometry and texture creation depends on carefully selecting the parameters during the processing of images in photogrammetry software. The high or low resolution of geometry and texture has to be evaluated in relation to the final application and experience requirements. For the use of 3D models in research, conservation, or restoration, high-resolution models will be required. For the purpose of museum presentation, only high-resolution texture could be enough with a low-resolution geometry of the 3D model.

Image balancing

Balancing of captured images in post-processing can be avoided if the natural lighting conditions are favorable for photogrammetric images or by properly illuminating the object with special lighting in order to have a uniform distribution of light through the entire framed area. With good lighting conditions, the images suitable for photogrammetry can be captured by fixing all the parameters except the shooting time. Under/over expositions can be avoided by allowing the camera to adjust the shooting time automatically. However, if the shooting time is too high a tri/monopod is required for avoiding blurred images. The other parameter that can be adjusted manually is the autofocus, which can be centered on the most important details in the image framed area.

Nonetheless, in all shooting sessions, the images must be saved in the RAW image format of the camera manufacturer for enabling possible post-processing. Specifically, when image balancing is required due to unsuitable lighting conditions. The whole dynamic range captured by the camera sensor is maintained by capturing images in RAW format, which allows the balancing of the images in case of non-uniform light distribution throughout the photogram. Such image balancing can be carried out by image manipulation software such as Adobe Lightroom.

Processing

The automatic photogrammetric processing of captured images includes:

- image alignment for automatic estimation of corresponding features on captured images (tie points)
- calculation of reprojection error and iteratively improving the tie point orientation with bundle adjustment
- image matching to generate a dense point cloud
- scaling of dense clouds by detecting the physical targets or with a laser scan
- creation of 3D mesh

- creation of 3D texture

The selection of different parameters during the processing of images with automatic photogrammetry software determines the quality/resolution of geometry and texture of the resulting 3D model. Depending on the final use and required experience, the quality and resolution of 3D models can be selected at this step.

Number of polygons

The image matching process can be performed after properly orienting the images in 3D space. For every image set, the image matching process generates a 3D point for each pixel or group of pixels recognized in other images of the same set. This process can easily produce millions of 3D points even for a few images. The density of these 3D points can be manipulated by changing the image matching parameters in an image matching software. This step is followed by 3D mesh generation, which is theoretically twice the number of points in the dense cloud. But most of the programs for mesh generation generally use a mesh simplification algorithm to adapt the size of the polygon to the size of the represented feature or smoothing of the resulting mesh. Therefore, the resulting mesh typically contains a maximum of 50% more polygons than the number of points in the dense cloud.

The resolution of 3D geometry must be selected based on the final use and type of digitized object. In table 3 the resolution of the 3D model is categorized into high (> 4 million polygons), medium (< 4 million polygons), and low(< 1 million polygons).

Quality of texture

The final stage of 3D model generation is texturing of a 3D model with the images used for creating the geometry. The process of mapping the 2D texture on a 3D surface is called UV mapping, which is a standard process in computer graphics. U and V are the axis that defines a square area over which the 3D model is unwrapped. This creates a mapping between the 3D surface and the 2D area of UV space. The sides of UV space are usually a power of two i.e. 4096 x 4096 (4 Megapixel), 8192 x 8192 (8 Megapixel), and so forth. At the end of this process, all of the model surfaces have a correspondence with the pixels of this square image.

The selection of texture resolution depends on the final use and type of digitized object. Some examples of CH objects in which high-quality texture (≥ 16 megapixels) is required are medium-sized objects with high details, large-sized objects with medium details, and large-sized objects with high details. Medium quality texture (= 8 megapixels) can be created for small-sized objects with high details, large-sized objects with small details, and medium-sized objects with medium details. While low-quality texture (= 4 megapixels) could be sufficient in the case of small-sized objects with low details, small-sized objects with medium details, and medium-sized objects with low detail.

Post-processing

The final step of the 3D model production pipeline is the post-processing of the textured model from photogrammetry. This step includes the decimation of a 3D model and linking the model with narratives, metadata, and paradata. The post-processing step depends on the type of final application and the requirements of use. Several commercial software and online platforms can be used for 3D model decimation and annotation.

Decimation

The decimation of 3D models is required for several applications such as virtual reality, publication of 3D models online, and augmented reality. Before starting the process of mesh simplification, the meshes generated by photogrammetry must be examined for possible topological errors. Some examples of such errors include duplicate faces, duplicate vertices, unreferenced vertices, zero area faces, non-manifold edges, and non-manifold vertices. After removing the topological errors, the 3D mesh can be decimated by using several methods such as vertex clustering, incremental decimation, resampling, and mesh approximation.

In Table 6.3, the decimation of 3D models is divided into three categories i.e. high (< 1 million polygons), medium (< 4 million polygons), and low (> 1 million polygons). To obtain a highly decimated 3D model, more time for processing is required compared to medium decimation. Some examples of final uses in which high decimation is required are the uploading of 3D models on websites, and real-time engines. For rendering of 3D models for videos and augmented reality applications, medium decimation is required. For some uses, the decimation of 3D models is not recommended. Some examples of such uses are: digital archiving, digital restoration and monitoring of endangered CH, reconstruction of lost CH, archeological research

Annotation, metadata, and paradata

The final phase of post-processing is to create a structured database of 3D models by linking 3D models with annotations, metadata, and paradata.

An annotation in a 3D model means linking a portion of the model to the specific information related to that portion. Annotations have been used for a long time in 2D technical drawings with related legends. With 3D digitized models, the annotations provide much wider opportunities. Annotating a 3D model includes the selection of a specific region over the surface of the model and creating a link between that region and structured, semi-structured, or unstructured data. An annotation usually provides a characterization of a selected region such as material, sign/marking, structural/functional information, sub-component information, and insights of analyses for that specific area [Ponchio et al. 2019].

Metadata is the semantic description of the digitized object through appropriately descriptive attributes useful for searching the object in a database. Such attributes are data describing other data (i.e., the actual 3D digital content), and for this reason, are called “metadata” [Guidi and Frischer 2020; Guidi et al. 2015b]. Paradata, on the other hand, is the technical descriptions of the process and the equipment used for obtaining that particular digital content.

Annotated models along with descriptive metadata and the corresponding paradata can be used to create different layers of narratives for the final uses of 3D models of CH. Some examples where extensive annotations, metadata, and paradata are required are educational applications, restoration, preservation, and research. For online museum websites and interactive museum exhibitions, limited annotation and associated data can be enough.

6.2 Applicability of the 3D-CultEx framework

In the following subsections, the 3D-CultEx framework is applied to two different projects to understand its applicability and how it can evaluate a project involving 3D digitization for enhanced cultural experiences. Even though the selected projects have already been developed and presented in chapter 3, this section examines their positive aspects and evaluates shortcomings on the bases of the proposed framework. The evaluation of these projects also serves as an example of applying the proposed framework to any other project.

The projects being analyzed by the framework are PERVIVAL and Cultural Heritage Through Time CHT2 project. These projects include different types of digitized CH assets and different end-uses. The framework is being applied step by step from experience and interaction design to the quality of 3D digitized assets.

6.2.1 PERVIVAL evaluation

The PERVIVAL project was created to effectively explain a complex museum collection to its visitors through an interactive digital application. It is a learning application with the aim of creating a link between physical objects with their intangible characteristics to enhance the visitors' understanding of the funerary rituals of ancient Egyptians. The application presents multiple objects with rich symbolism and interconnection between them. Such interconnections create a story that allows a much greater understanding of the museum collection, which can be perceived as a whole by the visitors instead of looking at the isolated pieces.

Following is the evaluation of the PERVIVAL application by analyzing its different aspects through the 3D CultEx framework.

Design for experience

The application was designed to satisfy various needs of contemporary museums in Italian and European contexts. The objectives of the project are:

- maintain a low development, implementation, and maintenance cost
- limit the use of physical space
- avoid assembly of people for a long time
- creating personal experiences
- develop a tool for both technologically skilled and non-skilled end-users

Considering all these aspects an interactive touch screen was installed in the museum exhibition, which is more accessible in terms of implementation and user interaction, rather than immersive technologies.

Stakeholders

An interdisciplinary team composed of designers, engineers, archeologists, and museum professionals was employed for designing and implementing the experience through the PERVIVAL application. This is consistent with what has been explained in the 3D CultEx framework.

On the other hand, even though the visitors were interviewed after the implementation and their experience was evaluated afterward (see chapter 5), they were not involved in the designing phase. This consideration must be taken into account for future projects to implement enhanced experiences for a similar type of experience.

Context of use

The context of use in the case of PERVIVAL application is museum presentation and education. According to the framework presented here, such application must present the historical, political, spiritual, and artistic context of the museum objects, which has been successfully done in the PERVIVAL application.

As explained before, the PERVIVAL application presents the museum objects in context with their intangible characteristics through narratives linked to 3D digitized objects. Through the application, the visitors can explore the use of the funerary objects/furnishings to learn about the complex funerary rituals of ancient Egyptians. Each element in the remains of ancient Egyptian culture has a specific meaning and is linked to other elements by a network of semantic values, which together form the funerary rituals. The application aims at explaining such complex links, forming the rituals, in a simple way through a narrative map with three key points:

- Preserve the body through mummification, coffin, sarcophagus, and an appropriate tomb
- Feed the deceased with real or represented food
- Face ordeals with the help of rituals, amulets, and coffin decorations

The three key points alongside the objects to be explored can be seen in Figure 6.5.

Figure 6.5. A screenshot of the homepage of the PERVIVAL application representing an interconnection between different objects in a museum collection.

User context

As defined in this section of the presented framework, the users of the PERVIVAL application can be categorized as the end-users who do not directly interact with the physical artworks i.e. the museum visitors. The experiences must have been designed in the context of their needs, motivations for a museum visit, emotions, backgrounds, and expectations.

Even though some considerations were made based on literature, the actual end-user context was not analyzed before designing the digital experience in the PERVIVAL application. Therefore the latter analyses of visitor interaction data and interviews revealed several flaws in terms of experience design.

The shortcomings in pre-designing the experience based on the actual museum audience included: unsuitable experience for the majority of the visitors (teenagers and children accompanied by the parents); design of application interface (not easily understandable by the majority of inexperienced visitors), selection of digital items (excessive text) and levels of interaction with 3D models (see chapter 5 for details of visitor data analysis of PERVIVAL).

System Design

Without evaluation of the actual end-users, the application was designed by interdisciplinary researchers. Most of the aspects were designed based on literature and best practices from the past.

Therefore, the technical aspects such as creating an original feel through appropriate materials, geometry textures and scale digital 3D models presented in the application were some of the positive aspects of this application. Furthermore, based on the best practices, some of the formal aspects such as aesthetics and hygiene were also considered at the stage of experience development (Figure 6.6).

Figure 6.6. visitors interacting with the application with disposable gloves. The area highlighted in red provides hygiene instructions and necessary materials such as gloves and disinfectants.

On the other hand, due to the lack of prior end-user data, some of the formal aspects of system design such as accessibility, flexibility, and affordance of the application were not designed properly (Figure 6.7). Some examples of such shortcomings in the formal aspects of the interface design for digital experience include:

- non-intuitive access to different pages and sections of the application
- digital items selection in the right places (for example excessive or insufficient text on some pages)

- interaction with the 3D models was not designed properly for the visitors previously unfamiliar with such interactions

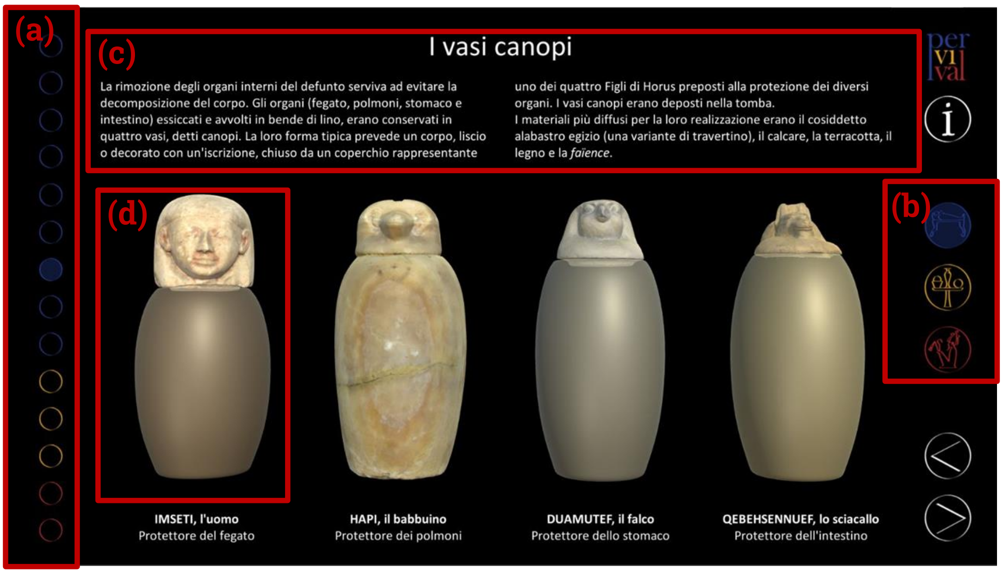


Figure 6.7. Some aspects of the PERVIVAL application interface referring to shortcomings of experience design: (a) access to different pages to the application; (b) direct access to three sections of the application; (c) introduction to the page and displayed content in form of text; (d) 3D model of a museum object with animations not controllable by the users.

Design for interaction

The pages in the PERVIVAL application were divided into four levels of interaction modalities. The users of the application can personalize their navigation approach depending on the level of interest and available time.

Level 1 provides the textual description of the main sections of the collection with an interactive glossary of words. Such pages do not contain any 3D interaction and are accessible both through pre-defined paths and direct selection of the main pages (Figure 6.8).

Figure 6.8. An example of the level 1 pages in the PERVIVAL application.

The pages on level 2 of the application include the textual description of the main objects in the collection and provide three levels of interaction depending on the importance and complexity of the objects. The pages with important objects do not have any interaction as they are further explained in the level 3 pages. Other important objects with no supplementary pages in level 3 have low interaction via quick overview animations in level 2 pages. The pages with objects having multiple digital representations allow full user interaction through an image scroll panel (Figure 6.9).

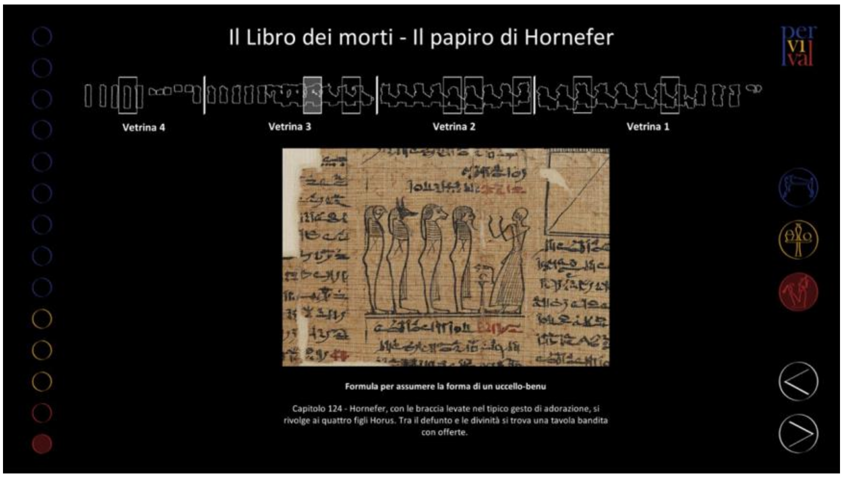


Figure 6.9. An example of the level 2 pages representing a selection of vignettes from the Book of the Dead with full interaction in PERVIVAL application.

The pages at level 3 have the most degree of interaction among all types of pages (Figure 6.10). Through animations and interaction with 3D models, these pages allow the users to explore more about the objects presented in level 2 pages. The 3D interaction in these pages is limited by three tools i.e. hotspots to access level 4 pages, sliders to rotate the models and magnifying glasses for the zoom.

Figure 6.10. An example of the level 3 pages in the PERVIVAL application. The sarcophagus with full user interaction is represented on this page.

Finally, the level 4 pages include different media such as text, videos, and animations for exploration of in-depth details of specific aspects of an object (Figure 6.11). Such aspects include reconstruction techniques, medical analyses, and the meaning of symbols. These pages are without user interaction and can be accessed through the hotspots on level 3 pages.

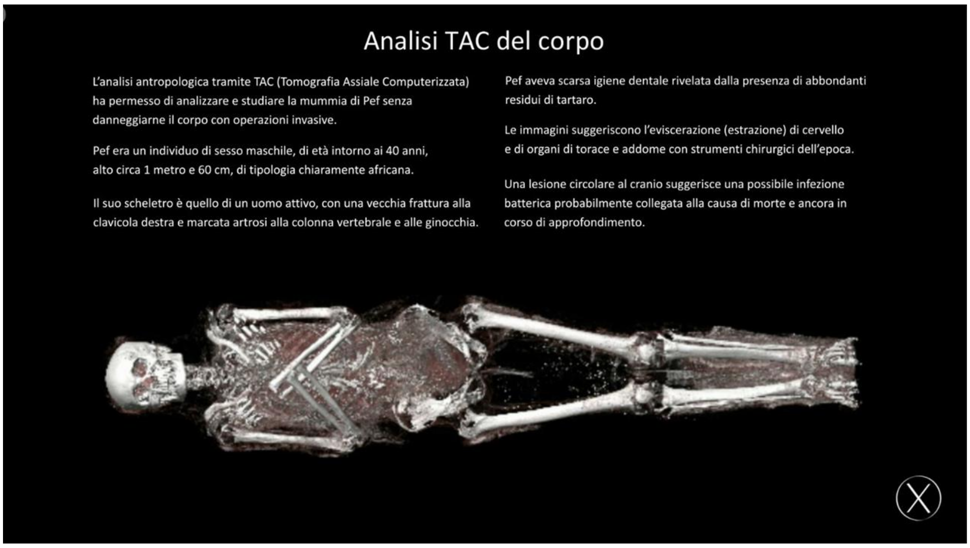


Figure 6.11. An example of the level 4 pages in the PERVIVAL application. The CT scanning analysis of the mummy is represented by an animation on this particular page.

Stakeholders

Similar to the first section of experience design, an interdisciplinary team also worked to design the interaction through PERVIVAL application, but the end-users feedback was not considered also at this step. Co-designing with the users (visitors in this case), also for the interaction development stage, is an important consideration to be taken into account for future projects.

Content selection

In the PERVIVAL application, the important tangible components of the museum collection were selected to be digitized to represent them with the intangible components of the same collection through narratives. To transform the archaeological studies into engaging narratives, the following grave goods from the Egyptian archeological collection were selected:

- the mummy and the painted coffin
- canopic jars
- amulets of different types
- ushabti
- false door stele
- papyrus representing the "book of the dead"

By evaluating the PERVIVAL application in terms of content selection through the presented framework, it is clear that the application succeeded to create simple narratives through digitized tangible content. But, it had a lack of the degree of interaction with the 3D models. The interactivity with 3D models in this application was limited to rotation with sliders and zooming with magnifying glasses. The full interaction was not provided as one would expect with a 3D model interactable on cellphone screens.

On the other hand, the digital items selected for presenting the intangible components of the collection were selected carefully and in accordance with the requirements of the experience. Such digital items included images, text, videos, 3D animations, 3D models of tangible components of the collection, and 3D models of reconstructions.

Interaction development

The interaction development stage for the PERVIVAL application is for the group of end-user experiences i.e. museum presentation/education. On the basis of the proposed framework, the end-user interaction must be evaluated in terms of visual and learning aspects.

The visual aspects of the interactive elements provided in the PERVIVAL application require improvement as they can sometimes create difficulty to find certain information, especially for the inexpert users. The affordance of some elements is not designed properly. For example, the hotspots and toggle buttons for in-depth exploration of information or sliders and magnifying glasses for interactive models, need improvement in terms of affordance for end-users (Figure 6.10). Similarly, the explorative nature of the application through a direct selection of pages or sequential exploration has also not been made very clear. Furthermore, on some occasions, there was excessive text on the pages which could be reduced or embedded in links for more curious users.

The learning aspects of the application, on the other hand, were designed properly by creating narratives of interconnection between physical objects and their intangible aspects through 3D digitized models and reconstructions.

Implementation

The implementation stage of interaction design also concerns the group of end-user experience. Therefore, according to the proposed framework, it must be evaluated in terms of museum goals, space design, and duration of the interaction.

Firstly, the PERVIVAL application was co-designed with the museum professionals, therefore the museum goals were considered also at the stage of implementation. In this specific case, the museum goals included:

- visitor education and engagement through narratives supported by reliable historical references
- consideration of the type of technology for various age groups of the visitors
- low budget and logistics

Secondly, the position of the digital screen of the PERVIVAL application in space was not convenient. It was placed directly on the opposite side of the physical objects, which made it difficult to connect the digital content to the physical object (one of the objectives of the PERVIVAL application). Some of the unrelated objects were also placed near the digital screen, a wastebin for example, which caused distractions and unpleasantness.

Finally, the proposed duration of interaction for complete navigation of the PERVIVAL application i.e. 20 to 25 minutes is too long. On the other hand, the time proposed for a synthetic overview of the application i.e. 3 minutes, is in accordance with the time that a visitor would spend on such an application. But the short synthetic overview of the application does not transfer the necessary learning content, which is the primary of the museum and the purpose of developing this application. The lengthy duration of interaction with such applications can become tiresome for the visitors and could be problematic also in terms of visitors' flow in the museum.

Such observations on implementation were recorded during the post-interaction interviews with the visitors of the PERVIVAL application (see chapter 5).

Quality of 3D models in PERVIVAL application

Most of the 3D models used in the PERVIVAL application were created by using digital photogrammetry. The pipeline for creating 3D models of objects, varying in sizes and complexity, was well optimized for the experience and interaction requirements of the PERVIVAL project discussed in previous sections. At each of the five steps of 3D model creation and optimization (assessment, setup, image capturing, 3D model creation, and post-processing), the optimal technical choices were made for the best compromise between quality, and total time spent for 3D model creation/processing and cost of equipment.

Assessment

The complexity of objects and working conditions were determined to be medium to low difficulty.

Setup

Two different sets of cameras and lenses were selected based on the assessment and many physical targets were used for scaling of 3D models

Image capturing

High-quality images were captured with a low GSD value and an optimal overlap between the consecutive images

3D model creation

Medium quality and processing time were selected for this step to achieve the required results.

Post-processing

The resulting 3D models were highly decimated to be used in a real-time engine and extensive annotations, metadata, and paradata were created to be used in an educational application.

All the choices made to achieve the best quality of 3D models in the PERVIVAL project are positioned in the quality matrix of the 3D CultEx framework (Table 6.4).

Table 6.4. The quality matrix of 3D model creation in the PERVIVAL project.

Assessment					Setup			Image capturing		3D model creation			Post-processing	
Size of object	Complexity (surface/shape)	Lighting conditions	Working conditions: Placement of object	Working conditions: Permissions	Camera and lens	Attachments	Targets for scaling	Number of images (overlap)	Image quality	Image balancing	Processing: Number of polygons	Processing: Quality of texture	Decimation	Annotation, metadata, and paradata
					• for medium complexity objects d) camera: Sony α6000 e) lens: Zeiss Touit 24mm f/1.8 f) attachment: none • for simple objects a) camera: Canon 5D Mark II digital reflex b) lens: Canon EF 20mm f/2.8 USM and Canon EF 50 mm f/1.8 c) attachment: none		many targets	medium (optimal) range of design factor q= 4.7–6.2	high-quality images for all the objects low GSD < 0.25 mm				high < 1 million poly. real-time engine	Extensive educational applications
medium < 4 m³ • sarcophagus • mummy - life-size artifact	medium Small details in medium-size objects	medium natural light indoors with windows and artificial lights								medium adjustment of exposure, brightness, and contrast in the RAW format from the camera	medium < 4 million • small-sized objects with high details • large-sized objects with small details • medium-sized objects with medium details	medium = 8 megapixel • small-sized objects with high details • large-sized objects with small details • medium-sized objects with medium details		
small < 1 m³ • canopic jars • amulets	low • smooth surface • rich texture		comfortable to reach • no obstruction around objects • low height objects	full no restrictions from the authorities or administrators										

Process duration

Total time of 3D model production

6.2.2 CHT2 evaluation

Under the scope of the Cultural Heritage Through Time (CHT2) project, a diachronic reconstruction approach was developed to show a lost monument in its current state and its presumed past appearance. The reconstructed monument was a late Roman Circus of Milan, with dimensions of ca. 70 x 460 meters. The reconstruction is based on a proper mix of quantitative data based on 3D surveys of its current condition, and on historical sources such as ancient maps, drawings, archaeological reports, laws regarding archaeological remains in the city, and old photographs. In this project, the georeferenced acquired 3D data of the remains played a crucial role in validating the previous reconstruction of the building and in defining some fixed points on which a reliable reconstruction covering different historical periods could be based.

The project was also presented in a museum exhibition through a video on a digital screen without any interaction with the user. The video guides the viewer through the steps, procedures, methodological approaches, and workflow for diachronically reconstructing the monument.

Following is the evaluation of the CHT2 project by analyzing its different aspects through the 3D CultEx framework.

Design for experience

The CHT2 project produced time-varying 3D products, from individual buildings to an entire landscape, with the objectives of:

- envisaging and analyzing lost scenarios
- visualizing changes due to anthropic activities or intervention, pollution, wars, earthquakes, or other natural hazards
- integrating the temporal dimension, its management, and visualization, for studying and analyzing Cultural Heritage structures and landscapes through time
- merging heterogeneous information and expertise to deliver enhanced four-dimensional (4D) digital products of heritage sites

The in-depth methodology and goals of the project are described in [Rodríguez-Gonzálvez et al. 2017]. The specific diachronic model of the Roman circus, developed as a result of this project, represents a tool for the dissemination of knowledge that is effective and adaptable to different types of use. The systematization of the data processing and the representations resulted in a new starting point for further specialized studies that could, for example, lead to new archaeological excavations aimed at defining missing or doubtful features in the reconstruction.

Stakeholders

An interdisciplinary team of designers, engineers, architects, archeologists, and museum professionals worked together to develop the diachronic 3D models for restoring the lost CH assets, which is in accordance with the criteria provided by the proposed framework.

Context of use

The context of use in the case of the CHT2 project is research, conservation, and restoration. According to the framework presented here, such projects must produce 3D models of high quality with integrated metadata, intangible characteristics of CH assets, and interdisciplinary information. Furthermore, the 3D models produced as a result of such projects must also be easy to explore and manipulate by the researchers. All of these aspects have been well considered in the creation of 4D models produced as a result of the CHT2 project.

High-resolution and accurate 3D models were produced to reconstruct the monument in the CHT2 project. The reconstruction is based on a proper mix of quantitative data based on 3D surveys of its current condition, and on data from historical sources (Figure 6.12). The methodology to reconstruct the monument included:

- bibliographical research to gather information about the studies and excavations carried out in the past on the monument and on the other similar structures of the same period.
- archival research for archaeological records, photographic archive, and archive of the restraining orders imposed on the owners of private houses in the area once occupied by the monument
- research of maps in the print archive
- updating the Territorial Database of the Municipality of Milan, which allowed the extraction of the most recent maps of the area of interest
- establishing the actual presence of remains, describing their state of conservation, to gauge the chances of undertaking a 3D survey
- 3D campaign for data collection
- integration of quantitative 3D data with the historical information in form of a parametric 4D model

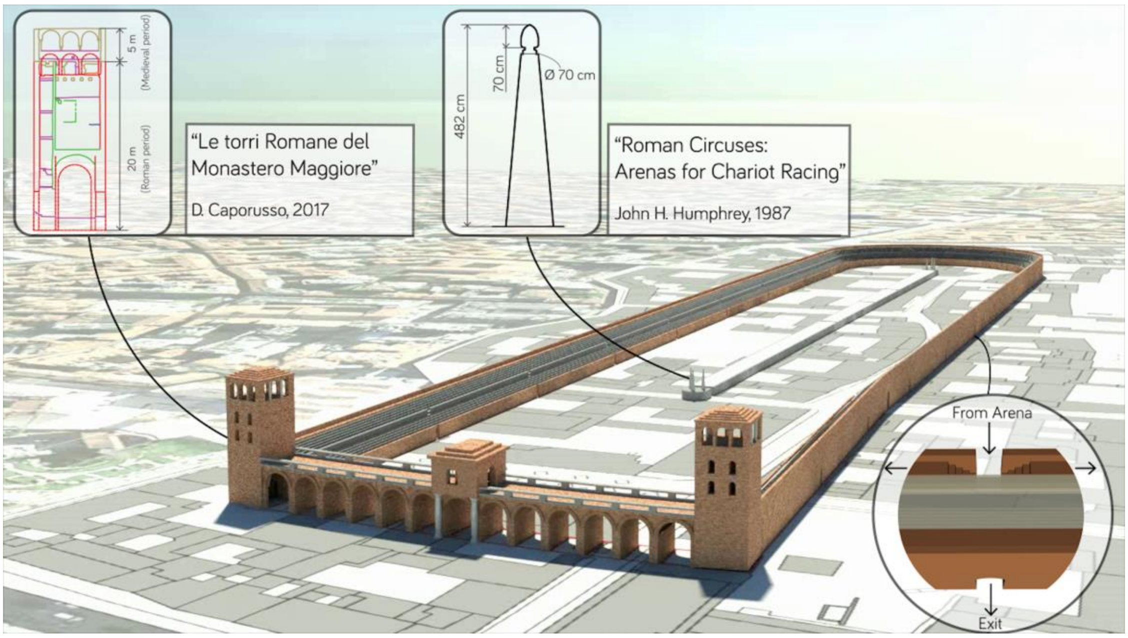


Figure 6.12. An example of heterogeneous data integrated with the high quality and precise 4D model produced in the CHT2 project.

Furthermore, the project produces textured parametric 4D models on the bases of georeferenced 3D digitization of the remains integrated with heterogeneous information from different sources. Such models were textured and parametric. Because of the parametric nature of the resulting models, they are transferable between several platforms and easily manipulatable by interdisciplinary researchers.

User context

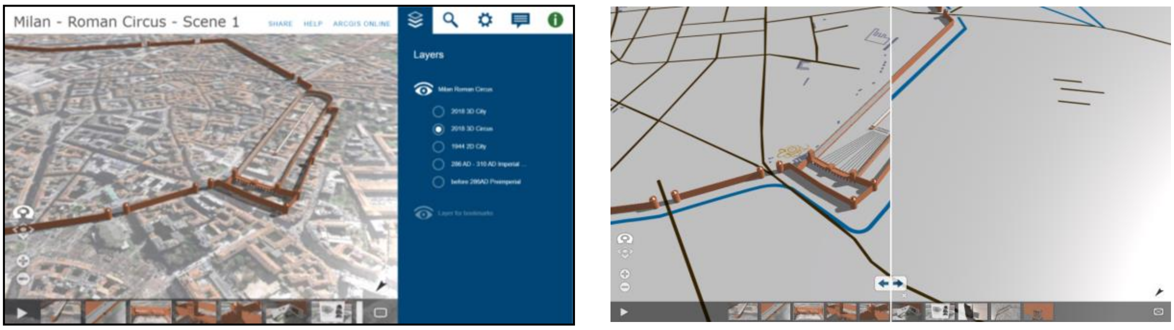
For this section of the framework, the users of the 3D models produced in the CHT2 project can be categorized as the professional users who directly interact with the physical CH assets i.e. the CH professionals and researchers. Therefore the final experience through 3D models must be designed in the context of their professional needs and expectations from the resulting tools.

As the CHT2 project was co-created with interdisciplinary researchers and professionals, their professional needs and expectations from the outcomes were well considered in accordance with the proposed framework. Some of these considerations are listed below:

- temporal analyses through multi-temporal 3D reconstruction for the preservation and maintenance of CH
- the study of the evolution of heritage sites for the development of hypotheses about the past and to model future developments
- the capacity of the 3D model to show the dynamic evolution of CH assets across different spatial scales
- providing the basis for decisions related to interventions and promotion of CH

System Design

The technical aspects of the system design were dealt with to a certain extent in the output of the CHT2 project. Several data optimization and visualization platforms were evaluated and adapted for professional users. Various practical tests were conducted with both commercial and open-source methods of 4D model publication. The solution that was mainly adapted is ESRI technology CityEngine web viewer - an open-source online platform [Esri 2020b]. This platform provides the possibility to visualize and compare the annotated 4D models of the monument with complex geometry, textures, scales, and context. Full integration of georeferencing 3D models with orthophoto maps, numerical terrain models, and other geo-referenced data is also possible on this platform (Figure 6.13a).



(a) (b)

Figure 6.13. The 4D model of the circus of Milan displayed on the CityEngine platform. (a) The reconstructed georeferenced 3D model of the circus with the current map of the city; (b) the slider function of the CityEngine platform to visualize the different states of the monument.

CityEngine viewer also provides a solution for simultaneous comparison of 3D models from two different time periods by providing the user an option to divide the screen into 2 parts and move the slider (Figure 6.13b).

Despite all the positive technical aspect, the solution adapted to display the outcomes of the project have some limitations regarding the visualization and management of huge datasets with a fluent real-time interaction. Even if optimized 3D models were used, the 4D models' visualization platform is not able to process the information in real-time and often results in slow data loading and system crashes. Because of such inability of built-in optimization of visualizations in the online viewer, it was not possible to upload the textured models on this platform (Figure 6.13a), which would have made it impossible to load with a normal broadband connection.

The formal aspects of accessibility and flexibility of the results in form of 4D models are in accordance with the proposed framework. The visualizer of 4D models works in the WebGL standard on computers, laptops, smartphones (on Android and iPhone), and in all browsers. Furthermore, despite the fact that ESRI technologies are commercial solutions, the CityEngine web viewer is free. The exported data can be placed directly on the private server without the need to purchase additional licenses. However, the interface design and affordance of the web viewer are not thought of properly for the users who are not familiar with the functionalities of such viewers.

Design for interaction

The results of CHT2 were disseminated in form of 3D and 4D models with four different modes of interaction.

The first mode of interaction was the publication of 4D models online as shown in Figure 6.13. An online web viewer is a tool that can be used by researchers and CH professionals not only for visualization but also for CH management and analysis. Various geo-referenced data with 3D models can be used to arrange the digital information for different purposes, such as studies, analyses, preservation, and simulations.

The second mode of interaction was created by optimizing the 3D models and converting them into a transferrable file format. The file format used for this purpose was .FBX, which is a patented format to provide interoperability between various digital content creation applications. The 3D model with optimized geometry and texture mapping in .FBX format (Figure 6.14) can be used across various real-time and gaming engines to develop AR and VR applications.

Figure 6.14. 3D model of the reconstructed circus in .FBX format with UV mapping.

The 3D models in the different time periods were also uploaded on Sketchfab.[36] Sketchfab also provides the option to annotate the 3D models and connect them to metadata and paradata. These annotated models can be used by researchers and CH professionals as a tool for archeological research and analyses.

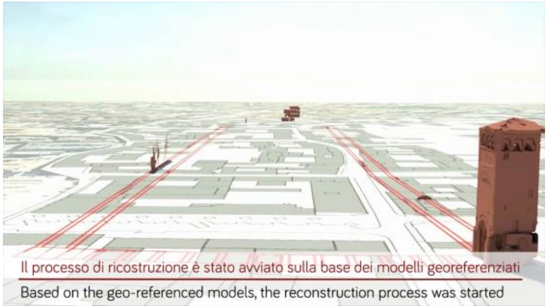
Figure 6.15. 3D model of the circus with city walls on the map of imperial Milan in the late Roman empire.

[36] https://sketchfab.com/3d-models/imperial-milan-286ad-310ad-26382ea7b4bc4b59bdbfe8fe29989cb0; https://sketchfab.com/3d-models/pre-imperial-milan-before-286ad-79e51c90df9a4329a05f34b27d785b50; https://sketchfab.com/3d-models/current-city-2018-5e067de18a8e4fb29e5ccb8edd6e03c6

Finally, the process of reconstruction and the sources used for such reconstruction was also demonstrated in form of a video (Figure 6.16). The video starts by showing the current situation of the urban fabric where the circus was once located. Then it demonstrates the identification of the areas where it is still possible to survey the remains of the monument. In the next step, the use of various 3D capturing and geo-referencing technologies is explained. Subsequently, the reconstruction of the monument based on the recorded 3D geo-referenced data integrated with the information from other sources has been displayed. The last step of reconstruction demonstrated in the video is a complete 3D textured model with the ancient city walls and their evolution over time. Finally, an animated simulation of paths taken by the chariots and audiences to enter and exit the circus has been added at the end of the video.

The detailed video can be found on the website of the archeological museum of Milan.[37]

(a)



(b)

(c)

(d)

Figure 6.16. Some screenshots from the video explaining the reconstruction of the monument by integrating various information and the dimension of time. (a) Current situation of the city where the monument was originally built; (b) georeferencing of 3D data of the remains; (c) reconstruction of details by integrating heterogeneous information with 3D data; (d) an animation simulating the path of chariots in the reconstructed 3D model of the monument.

Stakeholders

Similar to the first section of experience design, an interdisciplinary team also worked to design different modes of interaction with the diachronic 3D models of CHT2 projects. All the

[37] https://www.museoarcheologicomilano.it/scopri-il-museo/le-torri-romane-e-il-monastero-maggiore/la-torre-del-circo

stakeholders represented at this step in the 3D CultEx framework were involved accordingly in CHT2 project dissemination.

Content selection

The results of the CHT2 project, which included the digitized tangible remains of the monument along with the reconstruction hypothesis for different time periods, were disseminated through various means. Multi-temporal 3D reconstructions of the monument were used for the requirements of preservation, restoration, evaluation, analysis, and interventions. The selection of content for such purposes included:

- 3D reconstruction of the circus and ancient city walls
- georeferenced current and archived maps
- videos and photographs of different methods used for reconstructions and investigations
- animations to simulate functionalities of different features of the monument

In line with this section of the 3D CultEx framework, 3D models developed in the CHT2 project had the possibility to provide a full degree of interaction. As the results of the project were presented through different methods, the interaction with the reconstructed 3D models varied based on the specific method and purpose. The video, for example, served the purpose of iteratively simulating the reconstruction process and techniques, thus 3D models in the video were used to demonstrate the process without any user interaction. In contrast, 3D models presented in the 4D visualizer provided the users with a full degree of 3D interaction and explore the temporal dimension. Likewise, the annotated 3D models on Sketchfab provided the possibility of user interaction with the localized information on the surfaces of the 3D models.

The digital items selected for presenting the methodologies and reconstructions were also selected carefully and in accordance with the requirements of the experience. Such digital items included images, text, videos, 3D animations, 3D models of the remains, and 3D models of reconstructions.

Interaction development

The interaction development stage for the CHT2 project concerns the experience of professionals in research, conservation, and restoration. On the basis of the proposed framework, the interaction for professionals must be evaluated in terms of the needs and context of different professionals. Such needs and user context were well considered in the 4D reconstruction of the monument.

The shape, dimensions, and geometry of the monument were reconstructed as accurately as possible with the proper combination of quantitative data of the remains and historical information. The accurate reconstructed 3D models were produced in various historic contexts.

On the contrary, no accurate physical information on the appearance and materials of the monument were available through neither the historical sources nor the data acquired in fieldwork. Therefore, the materials applied to the reconstructed model were intended only to suggest a possible hypothesis of restoration of the original appearance of the monument. Such a hypothesis was developed with the approval of the experts in Roman archeology.

Furthermore, the temporal layers were added to the reconstructed 3D models. The reconstruction of the monument starting from the documentation provided from the past studies integrated with

3D surveys in the field and geographic information system was presented in different layers through the web visualizer displayed in Figure 6.13. Such 4D 3D representations, which define the variations in time of the area of interest, allow the users to interact with 4D urban landscapes by means of a common web browser on a computer and cellphone. Through this tool, it is possible to explore maps, display specific layers for individual historical periods, and enrich the experience with information linked to hot spots on the model. For example, as shown in Figure 6.13, different 3D layers can be seen at once by splitting the screen into two parts and navigating the two models at the same time and with the same point of view. This allows the user to better compare the same area in different periods.

Implementation

The implementation stage of interaction design for the CHT2 project also concerns the experience of professional users. Therefore, according to the proposed framework, it must be evaluated in terms of research/professional objectives, type of application, and accessibility for the professionals.

The project was co-developed with the archeologists and interdisciplinary researchers to include various objectives in the dissemination of the results. The results of the project provided different platforms for the professionals to analyze the monument, evaluate its past, support its promotion, and make decisions on future developments and interventions. Such dissemination of the results is in line with the evaluation criteria for the professional user objective delineated in the proposed framework.

Furthermore, most of the applications used for presenting the results of the CHT2 project are open source which makes them accessible for different professionals to study the 3D models coupled with various historical information. The results were disseminated in form of interactable 4D models to be used by the professionals in a simple manner for their daily practices.

Quality of 3D models in PERVIVAL application

Although most of the 3D surveys utilized active 3D sensing for reconstructing the form and orientation of the monument, the most useful contributions for the reconstruction of details came from the photogrammetric survey of a significant part of the outer circus wall remains. At each of the five steps of 3D model creation and optimization (assessment, setup, image capturing, 3D model creation, and post-processing), several technical choices between quality, total time, and cost of equipment were made for extracting different details from photogrammetric 3D models through orthophotos and integration of historical information into the resulting models. Such choices under the scope of the CHT2 project are represented in Table 6.5.

Assessment

Even though the size of the object to be digitized was large, the complexity was determined to be of low difficulty. It was difficult to reach some details due to obstacles and height, but there were no restrictions for surveying from authorities.

Setup

The camera was selected based on the assessment of the situation to capture photos outdoors and was coupled with a long monopod for shooting the details in high places. No targets were used for scaling and the resulting digital model was scaled by using a few measurements of prominent details in the scene.

Image capturing

High-quality images were captured with a low GSD value and an optimal overlap between the consecutive images for long-range photogrammetry.

3D model creation

High quality and processing time were selected for this step to achieve the required results.

Post-processing

The resulting 3D models were not decimated to be used for extracting exact details and dimensions from the remains for the reconstruction of the monument details. Extensive annotations, metadata, and paradata were integrated with the 3D model to be used for research-related purposes.

Table 6.5. The quality matrix of 3D models creation in CHT2 project.

Assessment					**Setup**			**Image capturing**		**3D model creation**			**Post-processing**	
Size of object	Complexity (surface/shape)	Lighting conditions	Working conditions: Placement of object	Working conditions: Permissions	Camera and lens	Attachments	Targets for scaling	Number of images (overlap)	Image quality	Image balancing	Processing: Number of polygons	Processing: Quality of texture	Decimation	Annotation, metadata, and paradata
large > 8 m^3 architectural scale			difficult to reach • at high place • details hidden by trees		for capturing details at high places without using the drone. d) camera: Sony NEX 6 e) lens: Zeiss Sonnar 24mm f/1.8 a) attachment: camera attached on a 6m monopod remotely controlled by a smartphone			medium (optimal)	high-quality images (low GSD)		high > 4 million large-sized objects with high details	High ≥ 16 megapixel large-sized objects with high details		**Extensive** For restoration/ preservation/ research
														
	low • rich texture • bricked walls	high natural light • outdoors with daylight		full no restrictions from the authorities or administrators			no targets architectural scale simple measurements were taken between prominent features			none direct use of photos from camera in .jpeg format			none > 1 million poly. • digital archiving • digital restoration and monitoring of endangered CH • reconstruction of lost CH • archeological research	

Process duration

Total time of 3D model production

7. CONCLUSIONS AND FUTURE WORKS

The research presented in this thesis is intended to respond to the lack of theoretical works in applying 3D digitization for enhanced cultural experiences. The evaluation of cultural experience, starting from good quality 3D models of CH assets, which emerged from this work has been presented in form of a theoretical framework. Such research is the first attempt to combine quantitative and qualitative research methodologies in the field of digital heritage and museum informatics. The mixed methods research attempted to answer the research questions proposed in chapter 1 related to:

- 3D digitization for enhanced cultural experiences
- best practices for 3D digitization of museum collections
- user interaction and perception of 3D digitized CH assets

7.1 Conclusions

In order to provide the answers, different projects developed during the course of this research were analyzed for improving the efficiency of 3D digitization and developing the evaluation criteria for user experience. The best practices in 3D digitization of CH and laboratory experiments were used to develop guidelines on the efficiency of the 3D digitization pipeline, while the perception of different technologies such as AR, VR, 3D printing, and touch screens, was studied by conducting mixed-methods research with different users of such technologies. The analyses of quantitative and qualitative data were integrated in form of a theoretical framework, which provides guidelines for obtaining the best quality 3D models of CH assets for designing user experiences for pre-defined uses. In addition, it provides a hybrid methodology for evaluating the digital experience effectiveness with different classes of users.

7.1.1 Projects for the enhanced cultural experience

The research started with the positioning of research in the related areas and by pointing out the gaps in existing literature in the areas related to “digital heritage” i.e. 3D digitization of CH and museum experience design (see chapters 1 and chapter 2). Four significant contexts (education, research, conservation/ restoration, and museum presentation) of using 3D digitization in CH were also defined at this step.

For exploring the best practices in 3D digitization of CH assets and analyzing its pre-defined uses, four different projects (IU-Uffizi, CHT2, PERVIVAL, LSI) developed during the course of this research were presented in chapter 3. Related to the first research question, these projects exploited various forms of 3D digitized CH assets from painting to sculptures to architectural scales for all the pre-defined uses of 3D digitization of CH. These projects were also used to answer the second and third questions of this research i.e. developing the guidelines of best practices in 3D digitization of CH assets and evaluation of user interaction and perception through qualitative and quantitative data collections from the stakeholders of this research.

7.1.2 Best practices in 3D digitization of CH and metrological guidelines

The second question regards the quality of 3D digitization of CH assets. The literature review in chapter 2 showed that photogrammetry is a rapid and preferred technique for the 3D digitization of CH assets. Therefore, in Chapter 4 several best practices and metrological guidelines were discussed to develop a pipeline for producing high-quality 3D models of CH assets through photogrammetry.

The first part of this section was related to the best practices in 3D digitization of the museum contents in different situations. At this point, several technical choices were discussed related to:

- Size and complexity of the objects
- Working conditions such as ambient lighting conditions, placement of objects, and permissions from authorities
- Processing of photos for the creation of textured 3D models. One of the important choices related to the 3D model processing was the use of a laser scan for scaling the 3D models instead of using the traditional method of scaling through physical targets.
- Post-processing digital 3D models of CH objects such as decimation, metadata, and paradata collection

Such technical choices were used to expedite the process of creating a huge amount of 3D models in less time without compromising the quality and to develop a reliable and efficient pipeline for the whole process of 3D model generation and pos-processing. This part was based on the technical choices adopted during the massive 3D digitization project of the Uffizi Gallery Museum in Florence Italy.

The second part of this section was related to the metrological guidelines for obtaining an improved quality of 3D models through the photogrammetric process. The specific aspect of the photogrammetric process that was discussed at this point was related to the image capturing protocol for close-range photogrammetry. This part analyzed the influence of the lateral displacement between adjacent images on the 3D quality of the dense cloud created from them by means of SfM/IM photogrammetry, in the case of highly convergent images typical of close-range photogrammetry on objects. Five different test objects were examined to estimate the influence of lateral displacement of images on the uncertainty of the photogrammetric point cloud. The objects made of rock differ in terms of stone type and visual appearance to simulate the surface properties of materials mostly used in CH objects. First, an accurate reference data set was generated by acquiring each object with an active range device, based on pattern projection. Then, each object was 3D-captured with photogrammetry, using a set of images taken radially, with the camera pointing to the center of the specimen. The camera–object minimum distance was kept constant during the shooting, and the angular displacement was as small as $\pi/60$. Several dense clouds were generated by sampling the original redundant sequence at angular displacements ($n\pi/60$, $n = 1, 2, \ldots 8$). Each 3D cloud was then compared with the reference, implementing an accurate scaling protocol to minimize systematic errors.

The residual standard deviation of the error made consistently evident a range of angular displacements among images that appear to be optimal for reducing the measurement uncertainty, independent of each specimen's shape, material, and texture. Different cases were compared through the parameter “q” (distance/baseline ratio or design factor). The results show that, for all the five test objects, low error conditions were found in the range of q = 4.7 - 6.2. Such a result provides guidance on how best to arrange the cameras' geometry for the 3D digitization of a stone cultural heritage artifact with several convergent shots. The experiments were performed under controlled conditions in the laboratory and the photogrammetric tool used in the experiments was Agisoft Metashape.

7.1.3 Mixed methods research for user interaction and perception

This part of the research attempted to answer the third question of this research related to user interaction and perception of 3D digitized CH assets. It aimed to get a better understanding of the applicability of various 3D technologies (AR, VR, digital screen displays, and 3D printing) for different purposes (education, research, conservation/restoration, and museum presentation), and to fathom the perception of these technologies. The data for this part was collected from the stakeholders of this research (researchers/ scholars, art historians/ archeologists / Museum professionals, designers, engineers/ digital application developers, and museum visitors) through questionnaires, interviews, collaborative workshop sessions, visitor interaction logging and direct observations of digital museum experience (see chapter 5).

The questionnaire and the results of the discussions among the stakeholders in a workshop revealed that although the participants from different groups have very diverse ways of approaching the questions asked, the majority of the participants that took part in this research considered the use of 3D technologies (either physical or digital) (very) useful for all of the purposes included in this research. Firstly, when designing the experience using these 3D technologies, it became clear that the quality of the experience depends on three main factors: users' context (background, needs, expectations, motivations, emotions), the context of use (why these methods are being employed) and on the design of the system (both formal and technical aspects of the system in which users interact with the technologies). Subsequently, this also influences the modes of interaction between users and 3D technologies. The analyses of collaborative sessions in the workshop revealed the importance of developing modes of interaction based on the needs of end-users (what they expect from a specific technology) and the museums' goals (how a specific technology can enable museums to reach more people). Secondly, although there is a lot of confusion about the term authenticity and its significance, it is a topic of great importance when 3D technologies are brought into play. It is evident that the reproduction cannot obtain the same material authenticity as can the original work of art, yet the use of 3D reproductions illustrates the importance of the original purpose of the objects, the context in which they were created, and their conceptual meaning. Albeit a reproduction cannot exactly correspond to the original, it appeared that for the perception of reproductions realism and similarity to the original were still highly desirable. The participants of the workshop all agreed that they did not want to be misled by a reproduction, yet it should have a realistic feeling to it in order for the reproduction to blend into the context and mean something in reference to the original. In this regard, for an authentic experience, the decisions must be made based on the extent to which we make it high fidelity versus demonstrating that it is actually a copy.

The preliminary observations through the workshop were then validated based on the input from the end-users i.e. museum visitors. For this purpose, visitors' feedback was collected in terms of the experience of interacting with an application utilizing the 3D digitization of museum objects. As a case study, the data was collected through interviews, questionnaires, and direct observations of the usage of the digital interactive application "PERVIVAL", which has been installed in the archeological museum of Milan. The user data was collected by carefully designed semi-structured Interviews, questionnaires, and visitors' interaction logging which were then integrated with the physical observations. The analysis of the data collected from this case study provided the evaluation criteria for digital experience and interaction with the 3D content of CH.

The evaluation was grounded in quantitative and qualitative data collected from the visitors (analysis of visitors' navigation, their suggestions during the interviews, and their thoughts on the overall experience). Three important factors of interaction design emerged from such evaluations including the content selection, the design, and the implementation of interaction:

- among various types of digital items, the interactive 3D content resulted as the most effective tool for museum education
- thoroughly designing the visual and learning aspects of digital applications were considered the two main aspects of designing user interaction
- important aspects of implementing a digital museum interaction were the duration of the experience, understanding of the user context, and space design

7.2 Specific contributions

The research presented in this thesis has been conducted through a combination of quantitative and qualitative research methods to broaden the role of important stakeholders in the design, implementation, and evaluation of scenarios involving the intersection of museum experience with 3D technology.

The technical component of this research is related to the quality of the 3D digitization process. The use of photogrammetry for obtaining textured 3D models of CH has been well established in the past and all the procedures and protocols have been well defined. This research dealt with the optimization of such protocols and presented a pipeline for systematic 3D digitization of CH assets through photogrammetry and related metrological guidelines for image capturing and 3D model scaling. Such a pipeline is specifically beneficial in terms of saving additional time and efforts when the purpose is to digitize a large number of objects in their original settings (e.g. in museum galleries for example).

The experiential component of this research is related to the evaluation of cultural experience with 3D digitized CH assets. The evaluation of visitor experience in interactive exhibitions is certainly not new in the field of museum studies. Many researchers have applied qualitative methodologies to understand the visitors' identity [Falk 2016; Bond and Falk 2013], motivations for visiting a museum [Ellenbogen et al. 2008; Fantoni et al. 2012], learning outcomes from interactives [Falk et al. 2004; Hornecker and Stifter 2006] visitors' preferences among various types of interactives [Lindgren-Streicher and Reich 2007], and testing the functionality of interactives [Hornecker 2008]. However, the mixed methods approach presented in this thesis is the first attempt to combine the quantitative aspects (related to the quality of 3D models as a starting point of interactive experience) with qualitative evaluations (related to the interactive user experience).

Furthermore, the evaluation and assessment of the complex connection between the technology and user experience presented in this thesis require considering the perspectives of different stakeholders. Therefore, by involving the four identified stakeholders, the evaluations presented in this research not only deal with the experience of the museum visitor but also provide evaluations on how digital/physical 3D interactions with CH assets can support the activities of the researchers and CH professionals. For this purpose, various 3D technologies (AR, VR, digital screens, and 3D printing) were evaluated to understand the needs of various users (both professionals and visitors) and how they perceived these technologies in different contexts.

The main contribution of this thesis is a theoretical approach to studying digital heritage (specifically the use of 3D digitization in significant cultural contexts), which, up to now, has been mainly experimented with on practical grounds without conducting theoretical assessments. In particular, this research has proposed a theoretical framework that integrates evaluations carried out to answer the research questions on user experience and quality of the 3D digitization process combined with the lessons learned from literature (see chapter 6).

Such a framework can be beneficial for the professionals and researchers in the fields related to digital heritage for future research and designing cultural experience solutions with technology. Due to the fact that every museum is different, every technology is different, and every approach is different, the pieces of evidence from the past experiences cannot be replicated every time to predict the success of future developments. Nevertheless, it's important not to reinvent the wheel every time and use the past experiences as guidance on how to avoid common mistakes or to understand the challenges in the development and implementation of technology. A significant amount of time and resources can be saved by taking into consideration what has already been learned from past experiences and shared knowledge, instead of starting every time from scratch. The theoretical framework presented in this research does exactly that. It provides a common language to foster collaborations between interdisciplinarity researchers and practitioners such as designers, developers, and cultural heritage professionals. The researchers and practitioners can use this framework to get awareness about important aspects to consider for more conscious decisions related to interaction design for the cultural experience.

As already stated in the introduction, grounded in the evaluation of user data, the framework is intended to be theoretical. It should be able to suggest possible design choices for developing cultural experiences through 3D interactions. In the course of this research, no specific tools were developed to apply the specific criteria for designing cultural experiences through 3D digitization. Nevertheless, the framework provides foundations for the aspects that characterize the design of 3D interactions for CH. Therefore, the framework could also be considered an applicative framework. Such applicability was demonstrated by evaluating two past projects based on the criteria provided by the proposed framework.

Several sections of this thesis have been introduced through journal and conference publications as a contribution impact.

7.3 Limitations and future research

The research presented in this thesis is interdisciplinary in nature dealing with the complex interconnections between different disciplines and competencies related to engineering, humanities, and design. On one hand, it can be seen as an advantage because the interdisciplinarity helps to overcome the limitations of disciplinary perspectives by using theoretical frameworks from different disciplines and by creating a common language to explain a phenomenon [Aboelela et al. 2007]. On the other hand, the added complexity of interdisciplinary research requires oversimplifying or neglecting certain aspects belonging to intersecting disciplines. This limit has particularly been inevitable in this research due to the complex interdisciplinary nature of this research and the limitation of available time and resources. But, these limitations can be an opportunity for future research to deepen the analyses on certain aspects of the fields related to this research.

One of these simplifications made in the quantitative section of this research is related to the consideration of only a photogrammetric pipeline for the systematic 3D digitization of CH assets. Such process optimization pipeline is mainly based on only one project (the IU-Uffizi project), which dealt with digitizing most of the objects belonging to a single form of art, i.e., sculptural heritage. Though it is true that photogrammetry is the most practical and principal approach for the digitization of CH assets, especially for massive digitization with limited resources. But, photogrammetry is not the only technique that can be used for this purpose. For example, the 3D Petrie Museum project developed digital 3D applications based on the systematic 3D digitization of museum objects by using color laser scanning [UCL 2018]. Therefore, future research could benefit by strengthening the proposed pipeline by including the best practices for 3D digitizing through other active techniques of digitization (e.g. laser scanning) and experimenting with other forms of art (e.g. paintings) in real scenarios.

Secondly, some aspects were not considered during the data collection from the stakeholders of this research, which might have impacted the thoroughness of the proposed framework. For example, the evaluations of significance and experience were carried out through a study that was exploratory in nature. One obvious limitation is the fact that the insights in the personal context related to the perception of art and authenticity of the individual participants (stakeholders of this research) could not be provided. The focus was not specifically on the difference in the demography of the participants. What would be interesting for future research is to make a comparison between the perception of art and its authenticity between groups of different ethnic backgrounds, ages, and perhaps even gender. Similar to the quantitative section of this research, another limitation can be found in the fact that the qualitative study also used only a few forms of art. Further investigation can be done by doing more profound research into the perception of various 3D techniques in the case of other forms of art e.g. easel paintings. Using this research as a starting point, the comparison of the perception of easel paintings to the experience of the more three-dimensional case studies used here could be useful in understanding the effects of 3D technologies on individual art forms.

Furthermore, due to the pandemic, it was not possible to host many activities on-site. The participants of the workshop presented in chapter 5, for example, could not interact with the proposed digital applications in real life nor could they freely interact with and touch the physical replicas. This might have influenced the results of this research. For this reason, a deeper analysis of user experience can be performed in the future with similar collaborative sessions in the physical presence of the stakeholders.

Lastly, a part of this research also specifically evaluated the experience of 3D technologies for museum visitors with none or only limited prior knowledge of 3D methods and within a museum setting. But, the analysis of visitor learning and museum experience presented in chapter 5 is also based on only one type of digital application (PERVIVAL project) with a limited amount of museum artifacts. Such visitor analyses could have been more thorough by collecting additional data from the visitors in different museum settings with different 3D technologies. Though such activities were intended to be executed in different museums (Uffizi Gallery museum in Florence, Pinacoteca di Brera in Milan, and Rijksmuseum in Amsterdam), it was not possible to realize them during the course of this research. The main obstacle, apart from resources and timing, was the reluctance of museums to permit such activities due to privacy concerns, even if the proposals were only related to the data collection for research purposes.

8. REFERENCES

Dante Abate. 2019. Built-heritage multi-temporal monitoring through photogrammetry and 2D/3D change detection algorithms. *Studies in Conservation 64*, 7, 423–434.

Dante Abate, Fabio Menna, Fabio Remondino, and Maria Grazia Gattari. 2014. 3D PAINTING DOCUMENTATION: EVALUATION OF CONSERVATION CONDITIONS WITH 3D IMAGING AND RANGING TECHNIQUES. *International Archives of the Photogrammetry, Remote Sensing \& Spatial Information Sciences 45*.

Sally W Aboelela, Elaine Larson, Suzanne Bakken, et al. 2007. Defining interdisciplinary research: Conclusions from a critical review of the literature. *Health services research 42*, 1p1, 329–346.

Lien Acke, Kristel De Vis, Stijn Verwulgen, and Jouke Verlinden. 2021. Survey and literature study to provide insights on the application of 3D technologies in objects conservation and restoration. *Journal of Cultural Heritage* 49, 272–288.

Andrea Adami, Caterina Balletti, Francesco Fassi, et al. 2015. The bust of Francesco II Gonzaga: from digital documentation to 3D printing. *25th International CIPA Symposium 2015*, 9–15.

Anne Adams, Peter Lunt, and Paul Cairns. 2008. A qualitative approach to HCI research. In: P. Cairns and A.L. Cox, eds., *Research Methods for Human-Computer Interaction*. Cambridge University Press, Cambridge, UK, 138–157.

Janice Affleck and Thomas Kvan. 2008. Memory capsules:Discursive interpretation of cultural heritage through new media. In: Y.E. Kalay, T. Kvan and J. Affleck, eds., *New heritage: new media and cultural heritage*. Routledge, London; New York, 92–111.

Irene Aicardi, Filiberto Chiabrando, Andrea Lingua, and Francesca Noardo. 2018. Recent trends in cultural heritage 3D survey: The photogrammetric computer vision approach. *JOURNAL OF CULTURAL HERITAGE 32*, 257–266.

Maher A R Sadiq Al-Baghdadi. 2017. 3D printing and 3D scanning of our ancient history: Preservation and protection of our cultural heritage and identity. *International Journal of Energy and Environment 8*, 5, 441–456.

Eleni Alexandri and Antonia Tzanavara. 2014. New technologies in the service of museum education. *World Transactions on Engineering and Technology Education 12*, 2, 317–320.

T Allard, M Sitchon, R Sawatzky, and R Hoppa. 2005. Use of Hand-held Laser Scanning and 3D Printing for Creation of a Museum Exhibit. .

Nancy Allen. 2000. Collaboration through the Colorado digitization project. *First Monday*.

Carol Andrews. 1994. *Amulets of ancient Egypt*. British Museum Press.

Anastassia Angelopoulou, Daphne Economou, Vassiliki Bouki, et al. 2011. Mobile augmented reality for cultural heritage. *International conference on mobile wireless middleware, operating systems, and applications*, 15–22.

Alessandra Antonaci, Michela Ott, and Francesca Pozzi. 2013. Virtual Museums, Cultural Heritage

Education and 21St Century Skills. *Learning & Teaching with Media & Technology*, 185–195.

Liliana Ardissono, Tsvi Kuflik, and Daniela Petrelli. 2012. Personalization in cultural heritage: The road travelled and the one ahead. *User Modeling and User-Adapted Interaction 22*, 1–2, 73–99.

David Armstrong, Ann Gosling, John Weinman, and Theresa Marteau. 1997. The place of inter-rater reliability in qualitative research: An empirical study. *Sociology 31*, 3, 597–606.

David Arnold. 2013. *3DCOFORM - project final report*. Brighton, UK.

David Arnold and Guntram Geser. 2007. *EPOCH - Research Agenda*. Brighton, UK.

Kathleen Arthur, Sherry Byrne, Elisabeth Long, Carla Q Montori, and Judith Nadler. 2004. Recognizing digitization as a preservation reformatting method. .

C Atzeni, J A Beraldin, G Guidi, M Pieraccini, G Capanni, and Others. 2001. Tutorial: 3D Acquisition Representation. *EVA Florence 2001 Tutorial*.

Gabriela Avram, Luigina Ciolfi, Simona Spedale, Deborah Roberts, and Daniela Petrelli. 2019. Co-design goes large. *Interactions 26*, 5, 59–63.

Ronald T Azuma. 1997. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments 6*, 4, 355–385.

Simone Baldissini and Marco Gaiani. 2014. Interacting with the Andrea Palladio Works: the history of Palladian information system interfaces. *Journal on Computing and Cultural Heritage (JOCCH) 7*, 2, 1–26.

C. Balletti, M. Ballarin, and P. Vernier. 2018. Replicas in cultural heritage: 3D printing and the museum experience. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 55–62.

Caterina Balletti and Martina Ballarin. 2019. An Application of Integrated 3D Technologies for Replicas in Cultural Heritage. *ISPRS International Journal of Geo-Information 8*, 6.

R Baribeau, M Rioux, and Guy Godin. 1992. Recent advances in the use of a laser scanner in the examination of paintings. *Restoration'92: conservation, training, materials and techniques: latest developments. Preprints to the conference held at the RAI International Exhibition and Congress Centre, Amsterdam, 20-22 October 1992*, 69–73.

Réjean Baribeau, Guy Godin, Luc Cournoyer, and Marc Rioux. 1996. Colour three-dimensional modelling of museum objects. In: *Imaging the past: electronic imaging and computer graphics in museums and archaeology*. 199–209.

Sally-Anne Barnes, Doris Eikhof, Erika Kispeter, and Ross Parry. 2018. *Mapping the Museum Digital Skills Ecosystem - One by One-Phase One Report*. .

Timothy D Barnes. 2013. *The new empire of Diocletian and Constantine*. Harvard University Press.

Herbert Bay, Tinne Tuytelaars, and Luc Van Gool. 2006. SURF: Speeded Up Robust Features. In: A. Leonardis, H. Bischof and A. Pinz, eds., *Computer Vision -- ECCV 2006: 9th European Conference on Computer Vision, Graz, Austria, May 7-13, 2006. Proceedings, Part I*. Springer Berlin Heidelberg, Berlin, Heidelberg, 404–417.

Mafkereseb Kassahun Bekele and Erik Champion. 2019. A comparison of immersive realities and interaction methods: Cultural learning in virtual heritage. *Frontiers in Robotics and AI 6*, 91.

Mafkereseb Kassahun Bekele, Roberto Pierdicca, Emanuele Frontoni, Eva Savina Malinverni, and James Gain. 2018. A survey of augmented, virtual, and mixed reality for cultural heritage. *Journal on Computing and Cultural Heritage 11*, 2.

H Russell Bernard and Gery Ryan. 1998. Text analysis. In: *Handbook of methods in cultural anthropology*. .

F Bernardini, H Rushmeier, I M Martin, J Mittleman, and Gabriel Taubin. 2002. Building a digital model of Michelangelo's Florentine Pieta. *Computer Graphics and Applications, IEEE 22*, 1, 59–67.

Fausto Bernardini and Holly Rushmeier. 2002a. The 3D Model Acquisition Pipeline. *Computer Graphics Forum 21*, 2, 149–172.

Fausto Bernardini and Holly Rushmeier. 2002b. The 3D Model Acquisition Pipeline. *Computer Graphics Forum 21*, 2, 149–172.

F Blais, J Taylor, L Cournoyer, et al. 2007. Ultra high-resolution 3D laser color imaging of paintings: the Mona Lisa by Leonardo da Vinci. *Castillego, et al.(eds.) Lasers in the Conservation of Artworks*, 435–440.

Nigel Bond and John Falk. 2013. Tourism and identity-related motivations: why am I here (and not there)? *International Journal of Tourism Research 15*, 5, 430–442.

Pierre Boulanger, Marc Rioux, John Taylor, and Forrest Livingstone. 1988. Automatic replication and recording of museum artifacts. In: *Analysis and examination of an art object by imaging technique*. 131–147.

James M Bradburne. 2001. A new strategic approach to the museum and its relationship to society. *Museum management and curatorship 19*, 1, 75–84.

Philipp Breuss-Schneeweis. 2016. " The speaking celt" augmented reality avatars guide through a museum case study. *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, 1484–1491.

John Brewer. 2000. *Ethnography*. McGraw-Hill Education (UK).

Emma Bryce. 2015. The British Museum uses 3D scanning to bring artefacts to life. *Wired*.

Ivan Burmistrov. 2015. Touchscreen Kiosks in Museums. .

Andres Bustillo, Mario Alaguero, Ines Miguel, Jose M Saiz, and Lena S Iglesias. 2015. A flexible platform for the creation of 3D semi-immersive environments to teach Cultural Heritage. *Digital Applications in Archaeology and Cultural Heritage 2*, 4.

Jorge Simarro Cabrera, Henar Muñoz Frutos, Adrian G Stoica, et al. 2005. Mystery in the museum: collaborative learning activities using handheld devices. *Proceedings of the 7th international conference on Human computer interaction with mobile devices \& services*, 315–318.

Giuseppe Caggianese, Pietro Neroni, and Luigi Gallo. 2014. Natural interaction and wearable augmented reality for the enjoyment of the cultural heritage in outdoor conditions.

International conference on augmented and virtual reality, 267–282.

Patrick Callet. 2014. 3D Reconstruction from 3D Cultural Heritage Models. In: *3D Research Challenges in Cultural Heritage*. 135–142.

Marco Callieri, Paolo Pingi, Marco Potenziani, et al. 2015. Alchemy in 3D: A digitization for a journey through matter. *2015 Digital Heritage*, 223–230.

Michael Calonder, Vincent Lepetit, Christoph Strecha, and Pascal Fua. 2010. BRIEF: Binary Robust Independent Elementary Features. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. 778–792.

Fiona Cameron and Sarah Kenderdine. 2007. *Theorizing digital cultural heritage: A critical discourse*. .

Marco Canciani, E Conigliaro, M Del Grasso, P Papalini, and M Saccone. 2016. 3D SURVEY AND AUGMENTED REALITY FOR CULTURAL HERITAGE. THE CASE STUDY OF AURELIAN WALL AT CASTRA PRAETORIA IN ROME. *International Archives of the Photogrammetry, Remote Sensing \& Spatial Information Sciences 41*.

Peter Cannon-Brookes. 1992. The nature of museum collections. In: J.M.A. Thompson, ed., *Manual of curatorship*. Routledge, London, 500–512.

Virginio Cantoni, Luca Lombardi, Alessandra Setti, Stanislav Gyoshev, Dimitar Karastoyanov, and Nikolay Stoimenov. 2018. Art masterpieces accessibility for blind and visually impaired people. *International Conference on Computers Helping People with Special Needs*, 267–274.

Alberto de Capitani d'Arzago. 1939. *Il Circo romano: Pref. del Prof. Aristide Calderini*. Ricerche della Commissione per la forma urbis Mediolani / Istituto di studi romani, Sezione lombarda; Ceschina.

D Caporusso. 2017. *Le torri romane del Monastero Maggiore: restauri, indagini e lettura storica*. Civico Museo archeologico.

A Capra, D Costantino, G Rossi, M G Angelini, and M Leserri. 2005. Survey and 3d modelling of Castel del Monte. *Proc. 20th Symp. Int. Coop. Save World's Cult. Heritage*, 183–189.

William Caraher. 2016. Slow archaeology: Technology, efficiency, and archaeological work. In: *Mobilizing the past for a digital future: The potential of digital archaeology*. The Digital Press at the University of North Dakota, 421–441.

Nicola Carboni and Livio De Luca. 2016. Towards a conceptual foundation for documenting tangible and intangible elements of a cultural object. *Digital Applications in Archaeology and Cultural Heritage 3*, 4, 108–116.

Julie Carmigniani and Borko Furht. 2011. Augmented reality: an overview. *Handbook of augmented reality*, 3–46.

Maria Beatriz Carmo and Ana Paula Cláudio. 2013. 3D virtual exhibitions. *DESIDOC Journal of Library and Information Technology 33*, 3, 222–235.

CECA. 2014. *ICOM Education 25 - Change of Perspective (New) ideas for representing museum objects*. .

CENSIS. 2015. *L'economia della disintermediazione digitale. 12° Rapporto Censis/Ucsi sulla comunicazione*. CENSIS, Rome.

Anna Ceresa Mori. 2018. Riflessioni sul palazzo imperiale di Milano alla luce delle recenti indagini. *Studia Ambrosiana 11*, 95–120.

Erik Champion and Hafizur Rahaman. 2019. 3D digital heritage models as sustainable scholarly resources. *Sustainability (Switzerland) 11*, 8.

Laura H Chapman. 1981. The future and museum education. *Museum News. The National Gallery of Art Washington, DC 60*, 6, 48–56.

Kathy Charmaz. 2006. *Constructing Grounded Theory*. SAGE.

Kathy Charmaz. 2009. Shifting the grounds: Constructivist grounded theory methods. *Developing Grounded Theory: The Second Generation*, 127–154.

Kathy Charmaz. 2014. *Constructing grounded theory*. sage.

Keith Cheverst, Nigel Davies, Keith Mitchell, and Paul Smith. 2000. Providing tailored (Context-aware) information to city visitors. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 1892*, August 2000, 73–85.

Omar Choudary, Vincent Charvillat, Romulus Grigoras, and Pierre Gurdjos. 2009. MARCH: mobile augmented reality for cultural heritage. *Proceedings of the 17th ACM international conference on Multimedia*, 1023–1024.

Carmine Ciavarella and Fabio Paterno. 2003. Design criteria for location-aware, indoor, PDA applications. *International Conference on Mobile Human-Computer Interaction*, 131–144.

CIDOC. 2012. *Statement of principles of museum documentation: CIDOC Documentation Standards Working Group*. .

Paolo Cignoni, Marco Callieri, Massimiliano Corsini, et al. 2008. Meshlab: an open-source mesh processing tool. *Eurographics Italian chapter conference*, 129–136.

A Cioci, A Spinetti, L Carosso, and C Atzeni. 2005. Digital three-dimensional modeling of heritage by frequency-modulated laser radar: the case of Donatello's David. *The 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage*.

Luigina Ciolfi and Liam Bannon. 2002. Designing Interactive Museum Exhibits: Enhancing visitor curiosity through augmented artefacts. *Eleventh European Conference on Cognitive Ergonomics*.

Luigina Ciolfi, Daniela Petrelli, Fiona Mcdermott, and Gabriela Avram. 2015. Co-design to Empower Cultural Heritage Professionals as Technology Designers. In: *Co-design to Empower Cultural Heritage Professionals as Technology Designers*. .

Paolo Clini, Mohamad El Mehtedi, Romina Nespeca, Ludovico Ruggeri, and Elisa Raffaelli. 2018. A digital reconstruction procedure from laser scanner survey to 3d printing: the theoretical model of the Arch of Trajan (Ancona). *SCIRES-IT-SCIentific RESearch and Information Technology 7*, 2, 1–12.

Erin Coburn and Murtha Baca. 2004. Beyond the gallery walls: Tools and methods for leading end-users to collections information. *Bulletin of the American Society for Information Science and Technology 30*, 5, 14–19.

Andrea Cohen, Christopher Zach, Sudipta N Sinha, and Marc Pollefeys. 2012. Discovering and exploiting 3d symmetries in structure from motion. *2012 IEEE Conference on Computer Vision and Pattern Recognition*, 1514–1521.

Alvaro Collet, Ming Chuang, Pat Sweeney, et al. 2015. High-quality streamable free-viewpoint video. *ACM Transactions on Graphics 34*, 4, 1–13.

Juliet Corbin and Anselm Strauss. 1990. Grounded Theory Research: Procedures, Canons, and Evaluative Criteria. *Qualitative Sociology 13*, 1, 3–21.

John W Creswell and Vicki L Plano Clark. 2017. *Designing and conducting mixed methods research*. Sage publications.

Areti Damala, Eva Hornecker, Merel Van Der Vaart, Dick Van Dijk, and Ian Ruthven. 2016. The Loupe: tangible augmented reality for learning to look at ancient Greek art. *Mediterranean Archaeology and Archaeometry 16*, 5, 73–85.

Areti Damala, I A N Ruthven, and E V A Hornecker. 2019. The MUSETECH Model: A Comprehensive Evaluation Framework for Museum Technology. *ACM Journal on Computing and Cultural Heritage 12*, 1, 1–22.

Areti Damala, Nenad Stojanovic, Tobias Schuchert, and Jorge Moragues. 2012. Adaptive Augmented Reality for Cultural Heritage : ARtSENSE Project. *EuroMed 2012: Progress in Cultural Heritage Preservation*, 746–755.

Jonathan Dandois, Marc Olano, and Erle Ellis. 2015. Optimal Altitude, Overlap, and Weather Conditions for Computer Vision UAV Estimates of Forest Structure. *Remote Sensing 7*, 10, 13895–13920.

Matteo Dellepiane, Nicolò Dell'Unto, Marco Callieri, Stefan Lindgren, and Roberto Scopigno. 2013. Archeological excavation monitoring using dense stereo matching techniques. *Journal of Cultural Heritage 14*, 3, 201–210.

Ahmet Denker. 2017. Rebuilding Palmyra virtually: Recreation of its former glory in digital space. *Virtual Archaeology Review 8*, 17, 20–30.

Biju Dhanapalan. 2016. Capturing kathakali: Performance capture, digital aesthetics, and the classical dance of India. *2016 22nd International Conference on Virtual System \& Multimedia (VSMM)*, 1–7.

Paolo Diacono--Paulus Diaconus. 2021. *Historia langobardorum*. Litres.

Paloma Díaz, Ignacio Aedo, and Merel van der Vaart. 2015. Engineering the creative co-design of augmented digital experiences with cultural heritage. *International symposium on end user development*, 42–57.

Lynn D. Dierking and John H. Falk. 1992. Redefining the museum experience: the interactive experience model. *Visitor Studies 4*, 1, 173–176.

Kosmas Dimitropoulos, Filareti Tsalakanidou, Spiros Nikolopoulos, et al. 2018. A multimodal approach for the safeguarding and transmission of intangible cultural heritage: The case of i-Treasures. *IEEE Intelligent Systems 33*, 6, 3–16.

Fulvia Donati. 2006. *L'archeologia e i suoi musei*. Servizio Editoriale Universitario, Pisa.

Pierre Drap, Julien Seinturier, Bilal Hijazi, et al. 2015. The ROV 3D Project: Deep-sea underwater survey using photogrammetry: Applications for underwater archaeology. *Journal on Computing and Cultural Heritage (JOCCH) 8*, 4, 1–24.

Ronald G Driggers. 2003. *Encyclopedia of optical engineering*. M. Dekker, New York; Basel.

Sandra Dudley. 2013. *Museum materialities: Objects, engagements, interpretations*. Routledge.

Daniele Duranti, Davide Spallizzo, and Raffaella Trocchianesi. 2016. Tangible Interaction and Cultural Heritage. An Analysis of the Agency of Smart Objects and Gesture–based Systems. *THE 6TH STS ITALIA CONFERENCE*.

Maria Economou. 1998. The evaluation of museum multimedia applications: lessons from research. *Museum Management and Curatorship 17*, 2, 173–187.

Sabry El-Hakim, J A Beraldin, F Remondino, Michel Picard, Luc Cournoyer, and E Baltsavias. 2008a. Using terrestrial laser scanning and digital images for the 3D modelling of the Erechteion, Acropolis of Athens. *DMACH Conference Proceedings, Amman, Jordan* November, 3–16.

Sabry F El-Hakim, Jean-François Lapointe, and Emily Whiting. 2008b. Digital Reconstruction and 4D Presentation Through Time. *ACM SIGGRAPH 2008 Talks*, ACM, 44:1----44:1.

Willemijn Elkhuizen, Tessa Essers, Yu Song, et al. 2019. Gloss, color, and topography scanning for reproducing a painting's appearance using 3D printing. *Journal on Computing and Cultural Heritage (JOCCH) 12*, 4, 1–22.

Kirsten Ellenbogen, John Falk, and Kate Haley Goldman. 2008. Understanding the Motivations of Museum Audiences. In: *Museum informatics: people, information, and technology in museums*. Taylor \& Francis, 187–194.

Kirsten M Ellenbogen. 2003. Museums in family life: An ethnographic case study. In: *Learning conversations in museums*. Routledge, 92–112.

EPOCH WEBSITE TEAM. 2004. EPOCH: Excellence in Processing Open Cultural Heritage. http://epoch-net.org/.

Esri. 2020a. ArcGIS CityEngine. https://www.esri.com/en-us/arcgis/products/arcgis-cityengine/overview.

Esri. 2020b. CityEngine Web Viewer. https://www.arcgis.com/apps/CEWebViewer/viewer.html.

EU Publications Office. 2008. 3D-COFORM: Tools and Expertise for 3D Collection Formation. https://cordis.europa.eu/project/id/231809.

European Commission. 2021. *Horizon Europe Work Programme 2021-2022. Annex 5: Culture, Creativity and Inclusive society work programme*. .

Europeana Foundation. 2008. EUROPEANA. https://www.europeana.eu/en.

James A Evans and Pat Sterry. 1999. Portable computers \& interactive multimedia: A new paradigm for interpreting museum collections. *Archives and Museum Informatics 13*, 2, 113–

126.

Allowen Evin, Thibaud Souter, Ardern Hulme-Beaman, et al. 2016. The use of close-range photogrammetry in zooarchaeology: Creating accurate 3D models of wolf crania to study dog domestication. *Journal of Archaeological Science: Reports 9*, 87–93.

Halina Ey-Chmielewska, Malgorzata Chrusciel-Nogalska, and Bogumila Fraczak. 2015. Photogrammetry and Its Potential Application in Medical Science on the Basis of Selected Literature. *ADVANCES IN CLINICAL AND EXPERIMENTAL MEDICINE 24*, 4, 737–741.

John H. Falk. 2016. *Identity and the Museum Visitor Experience*. Routledge.

John H. Falk and Lynn D. Dierking. 2016. *The museum experience revisited*. Routledge.

John H. Falk, Theano Moussouri, and Douglas Coulson. 1998. The Effect of Visitors ' Agendas on Museum Learning. *Curator: The Museum Journal 41*, 2, 107–120.

John H. Falk, Carol Scott, Lynn Dierking, Leonie Rennie, and Mika Cohen Jones. 2004. Interactives and Visitor Learning. *Curator: The Museum Journal 47*, 2, 171–198.

John H Falk and L D Dierking. 2003. Personal meaning mapping. *Museums and creativity: A study into the role of museums in design education*, 10–18.

John H Falk and Lynn D Dierking. 2000. *Learning from Museums: Visitor Experiences and the Making of Meaning*. AltaMira Press.

Silvia Filippini Fantoni, Rob Stein, and Gray Bowman. 2012. Exploring the relationship between visitor motivation and engagement in online museum audiences. *Museums and the Web*.

Francesco Fassi, Luigi Fregonese, Sebastiano Ackerman, and Vincenzo De Troia. 2013a. Comparison Between Laser Scanning and Automated 3D Modelling Techniques To Reconstruct Complex and Extensive Cultural Heritage Areas. *3D-ARCH 2013 - 3D Virtual Reconstruction and Visualization of Complex Architectures*, ISPRS, 73–80.

Francesco Fassi, Luigi Fregonese, Sebastiano Ackerman, and Vincenzo De Troia. 2013b. Comparison Between Laser Scanning and Automated 3D Modelling Techniques To Reconstruct Complex and Extensive Cultural Heritage Areas. *3D-ARCH 2013 - 3D Virtual Reconstruction and Visualization of Complex Architectures*, ISPRS, 73–80.

Francesca Fatta, Franz Fischnaller, and Belle Arti. 2018. Enhancing cultural heritage exhibits in Museum Education: 3D Printing Technology. *2018 3rd Digital Heritage International Congress (DigitalHERITAGE) held jointly with 2018 24th International Conference on Virtual Systems & Multimedia (VSMM 2018)*, IEEE, 1–4.

Marine Fau, Raphael Cornette, and Alexandra Houssaye. 2016. Photogrammetry for 3D digitizing bones of mounted skeletons: Potential and limits. *COMPTES RENDUS PALEVOL 15*, 968–977.

A Fedeli. 2015. Milano Archeologia. I luoghi della Milano antica. .

Anna Maria Fedeli and Ilaria Frontori. 2020. Mediolanum e l'acqua: alle origini di una millenaria convivenza. In: *Le forme dell'acqua. Approvvigionamento, raccolta e smaltimento nella città antica, Atti delle Giornate Gregoriane XII edizione (Agrigento 1-2 dicembre 2018)*. Bologna, 73–84.

Martin A Fischler and Robert C Bolles. 1981. Random Sample Consensus: A Paradigm for Model

Fitting with Applications to Image Analysis and Automated Cartography. *Commun. ACM 24*, 6, 381–395.

Franz Fischnaller. 2018. The Last Supper Interactive Project. The Illusion of Reality: Perspective and Perception. *5th INTBAU International Annual Event*.

Matthew Fisher and Beth A Twiss-Garrity. 2007. Remixing exhibits: Constructing participatory narratives with on-line tools to augment museum experiences. *Museums and the Web 2007: Proceedings*.

Raffaella Fontana, Marinella Greco, Marzia Materazzi, et al. 2002. Three-dimensional modelling of statues: the Minerva of Arezzo. *Journal of Cultural Heritage 3*, 4, 325–331.

Thomas Fotakis and Anastasios A Economides. 2008. Art, science/technology and history museums on the web. *International Journal of Digital Culture and Electronic Tourism 1*, 1, 37–63.

Fraunhofer Institute for Computer Graphics Research. 2018. Cultlab3D. https://www.cultlab3d.de/.

A. Freeman, S. Adams Becker, M. Cummins, E. McKelroy, C. Giesinger, and B. Yuhnke. 2016. *NMC Horizon Report: 2016 Museum Edition*. Austin, Texas.

Bernard Frischer. 2014. 3D DATA CAPTURE, RESTORATION AND ONLINE PUBLICATION OF SCULPTURE. *3D Recording and Modelling in Archaeology and Cultural Heritage*, 137.

Bernard Frischer, Georg Zotti, Zaccaria Mari, and Giuseppina Capriotti Vittozzi. 2016. Archaeoastronomical experiments supported by virtual simulation environments: Celestial alignments in the Antinoeion at Hadrian's Villa (Tivoli, Italy). *Digital Applications in Archaeology and Cultural Heritage 3*, 3, 55–79.

A Frova. 1990. Il circo di Milano e I circhi di età tetrarchica, in Milano capitale dell'impero romano (286-402 d.C.). *cat. della mostra, Cinisello Balsamo*, 423–431.

Yasutaka Furukawa and Jean Ponce. 2009. Accurate, dense, and robust multiview stereopsis. *IEEE transactions on pattern analysis and machine intelligence 32*, 8, 1362–1376.

Areti Galani and Jenny Kidd. 2019. Evaluating digital cultural heritage "in the wild": The case for reflexivity. *Journal on Computing and Cultural Heritage 12*, 1, 1–15.

Le Galleria degli Uffizi. 2021. The Uffizi Sculptures. https://www.uffizi.it/en/the-uffizi/sculpture.

Anne Galletta. 2013. *Mastering the semi-structured interview and beyond*. NYU press.

Christos Georgis and Ioannis Chrysakis. 2013. *3D-COFORM - Ingestion Tool User Manual*. Heraklion, Greece.

Andreas Georgopoulos. 2018. Contemporary Digital Technologies at the Service of Cultural Heritage. In: B. Chanda, S. Chaudhuri and S. Chaudhury, eds., *Heritage Preservation*. Springer Singapore, Singapore, 1–20.

Paola Di Giuseppantonio Di Franco, Fabrizio Galeazzi, and Valentina Vassallo. 2018. Why authenticity still matters today. In: *Authenticity and cultural heritage in the age of 3D digital reproductions*. McDonald Institute, 1–9.

Guy Godin, Jean-Angelo Beraldin, John Taylor, et al. 2002. Active optical 3D imaging for heritage applications. *IEEE Computer Graphics and Applications 22*, 5, 24–35.

Guy Godin, Marc Rioux, J A Beraldin, Marc Levoy, Luc Cournoyer, and François Blais. 2001. An assessment of laser range measurement on marble surfaces. *5th Conference on Optical 3D Measurement Techniques*, 49–56.

S. Gonizzi Barsanti, G. Caruso, L. L. Micoli, M. Covarrubias Rodriguez, and G. Guidi. 2015. 3D visualization of cultural heritage artefacts with virtual reality devices. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 40*, 5W7, 165–172.

Sara Gonizzi Barsanti, Laura Loredana Micoli, and Gabriele Guidi. 2013. Quick textured mesh generation for massive 3D digitization of museum artifacts. *2013 Digital Heritage International Congress (DigitalHeritage)*, IEEE, 197–200.

Eileen Hooper Greenhill. 1992. *Museums and the Shaping of Knowledge*. Routledge.

Armin Gruen, Fabio Remondino, and Li Zhang. 2003. Image-based reconstruction of the great Buddha of Bamiyan, Afghanistan. *Videometrics VII*, 129–136.

José Paulo Guerra, Miguel Moreira Pinto, and Cláudia Beato. 2015. Virtual reality-shows a new vision for tourism and heritage. *European Scientific Journal*.

G Guidi, L L Micoli, S Gonizzi, M Brennan, and B Frischer. 2015a. Image-based 3D capture of cultural heritage artifacts An experimental study about 3D data quality. *2015 Digital Heritage International Congress, Vol 2*, IEEE, 321–324.

G Guidi, R Trocchianesi, G Pils, G Morlando, and A Seassaro. 2010. A Virtual Museum for Design: New forms of interactive fruition. *16th International Conference on Virtual Systems and Multimedia (VSMM 2010)*, 242–249.

Gabriele Guidi, Carlo Atzeni, Maurizio Seracini, and Sara Lazzari. 2004a. Painting survey by 3D optical scanning: the case of “Adorazione dei Magi” by Leonardo da Vinci. *Studies in Conservation 49*, 1, 1–12.

Gabriele Guidi, Sara Gonizzi Barsanti, Laura Loredana Micoli, and Umair Shafqat Malik. 2017. Accurate reconstruction of the Roman circus in Milan by georeferencing heterogeneous data sources with GIS. *Geosciences (Switzerland) 7*, 3.

Gabriele Guidi, Sara Gonizzi Barsanti, Laura Loredana Micoli, and Michele Russo. 2015b. Massive 3D Digitization of Museum Contents. In: L. Toniolo, M. Boriani and G. Guidi, eds., *Built Heritage: Monitoring Conservation Management*. Springer, 335–346.

Gabriele Guidi, Jean-Angelo Beraldin, and Carlo Atzeni. 2004b. High-accuracy 3-D modeling of cultural heritage: the digitizing of Donatello’s “Maddalena”. *IEEE Transactions on Image Processing 13*, 3, 370–380.

Gabriele Guidi, Jean-Angelo Beraldin, and Carlo Atzeni. 2007. Wood artworks monitoring through high-resolution 3D cameras. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, SPIE, 1–7.

Gabriele Guidi and Bernard Frischer. 2020. 3D Digitization of Cultural Heritage. In: *3D Imaging, Analysis and Applications*. Springer, Cham, 631–697.

Gabriele Guidi, Umair Shafqat Malik, Bernard Frischer, Cristiana Barandoni, and Fabrizio Paolucci. 2018. The Indiana University-Uffizi project: Metrologica! challenges and workflow for massive 3D digitization of sculptures. *Proceedings of the 2017 23rd International Conference on Virtual Systems and Multimedia, VSMM 2017 2018-Janua*, September, 1–8.

Gabriele Guidi, Umair Shafqat Malik, and Laura Loredana Micoli. 2020a. Optimal Lateral Displacement in Automatic Close-Range Photogrammetry. *Sensors 20*, 21, 6280.

Gabriele Guidi, Umair Shafqat Malik, and Laura Loredana Micoli. 2020b. Optimal Lateral Displacement in Automatic. *Sensors*.

Gabriele Guidi, P Rodriguez Navarro, L L Micoli, S Gonizzi Barsanti, and M Russo. 2013. 3D Digitizing a whole museum: a metadata centered workflow. *2013 Digital Heritage International Congress (DigitalHeritage)*, IEEE, 307–310.

Gabriele Guidi, Daniele Ostuni, Fabrizio Costantino, Massimiliano Pieraccini, Grazia Tucci, and Jean-Angelo Beraldin. 2001. Photogrammetry and 3D scanning: Assessment of metric accuracy for the digital model of Donatello's Maddalena. *2001 Workshop of Italy-Canada on 3D Digital Imaging and Modeling Application of: Heritage, Industry, Medicine, & Land*, 1–8.

Gabriele Guidi, Fabio Remondino, Michele Russo, Fabio Menna, Alessandro Rizzi, and Sebastiano Ercoli. 2009a. A multi-resolution methodology for the 3D modeling of large and complex archaeological areas. *International Journal of Architectural Computing 7*, 1, 39–56.

Gabriele Guidi, Fabio Remondino, Michele Russo, and Alessandro Spinetti. 2009b. Range sensors on marble surfaces: quantitative evaluation of artifacts. *Proceedings of SPIE on Videometrics, Range Imaging, and Applications X*, SPIE, 744703–744712.

Gabriele Guidi, Michele Russo, and Davide Angheleddu. 2014. 3D Survey and Virtual Reconstruction of archeological sites. *Digital Applications in Archaeology and Cultural Heritage 1*, 2, 55–69.

Gabriele Guidi, Michele Russo, Sebastiano Ercoli, Fabio Remondino, Alessandro Rizzi, and Fabio Menna. 2009c. A Multi-Resolution Methodology for the 3D Modeling of Large and Complex Archeological Areas. *International Journal of Architectural Computing 7*, 1, 39–55.

Gabriele Guidi, Alessandro Spinetti, Luca Carosso, and Carlo Atzeni. 2009d. Digital three-dimensional modelling of Donatello's David by frequency modulated laser radar. *Studies in Conservation 54*, 1, 3–11.

Gabriele Guidi, Grazia Tucci, Jean-Angelo Beraldin, et al. 2002. Multiscale archaeological survey based on the integration of 3D scanning and Photogrammetry. *CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recording*, 13–18.

Daniel A Guttentag. 2010. Virtual reality: Applications and implications for tourism. *Tourism Management 31*, 5, 637–651.

N Haala and M Rothermel. 2012. Dense Multiple Stereo Matching of Highly Overlapping UAV Imagery. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XXXIX-B1*, 387–392.

Jong-Gil Han, Kyoung-Wook Park, Kyeong-Jin Ban, and Eung-Kon Kim. 2013. Cultural heritage sites visualization system based on outdoor augmented reality. *Aasri Procedia 4*, 64–71.

Laura K. Harrison. 2019. A roadmap to applied digital heritage: Introduction to the special issue on digital heritage technologies, applications and impacts. *Studies in Digital Heritage 3*, 1, 40–45.

Marc Hassenzahl, Sarah Diefenbach, and Anja Göritz. 2010. Needs, affect, and interactive products - Facets of user experience. *Interacting with Computers 22*, 5, 353–362.

Marc Hassenzahl and Noam Tractinsky. 2006a. User experience - A research agenda. *Behaviour and Information Technology 25*, 2, 91–97.

Marc Hassenzahl and Noam Tractinsky. 2006b. User experience - A research agenda. *Behaviour and Information Technology 25*, 2, 91–97.

Marek Hatala and Ron Wakkary. 2005. *Ontology-based user modeling in an augmented audio reality system for museums*. .

Anne-Cecilie Haugstvedt and John Krogstie. 2012. Mobile augmented reality for cultural heritage: A technology acceptance study. *2012 IEEE international symposium on mixed and augmented reality (ISMAR)*, 247–255.

Mona Hess. 2015. Online survey about current use of 3D imaging and its user requirements in cultural heritage institutions. *2015 Digital Heritage International Congress, Digital Heritage 2015*, IEEE, 333–338.

Mona Hess and Stuart Robson. 2013. Re-engineering Watt: A case study and best practice recommendations for 3D colour laser scans and 3D printing in museum artefact documentation. .

Mona Hess, Stuart Robson, Margaret Serpico, Giancarlo Amati, Ivor Pridden, and Tonya Nelson. 2016. Developing 3D Imaging Programmes--Workflow and Quality Control. *Journal on Computing and Cultural Heritage 9*, 1, 1–11.

Eilean Hooper-Greenhill. 1999. *The educational role of the museum*. Psychology Press.

Eilean Hooper-Greenhill. 2013. *Museums and their visitors*. Routledge.

Glen Hoptman. 1992. The virtual museum and related epistemological concerns. *Sociomedia-Multimedia, Hypermedia, and the Social Construction of Knowledge, ed. by Barrett, E.*, 141–159.

Eva Hornecker. 2008. “I don’t understand it either, but it is cool” - visitor interactions with a multi-touch table in a museum. *2008 3rd IEEE International Workshop on Horizontal Interactive Human Computer Systems*, IEEE, 113–120.

Eva Hornecker and Matthias Stifter. 2006. Learning from Interactive Museum Installations About Interaction Design for Public Settings. *Proceedings of the 18th Australia conference on computer-human interaction: design: activities, Artefacts and Environments.*, 135–142.

Xiaoyan Hu and Philippos Mordohai. 2012. A quantitative evaluation of confidence measures for stereo vision. *IEEE transactions on pattern analysis and machine intelligence 34*, 11, 2121–2133.

John H. Humphrey. 1986. *Roman circuses : arenas for chariot racing*. University of California Press.

Albert D Hunter and John Brewer. 2002. Multimethod research in sociology. In: *Handbook of mixed methods in social \& behavioral research*. SAGE Publications, Inc, 577–594.

ICOM. 2021. Museum Definition. *ICOM website*. https://icom.museum/en/resources/standards-guidelines/museum-definition/.

ICOMOS. 2003. *ICOMOS CHARTER- Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage*. Victoria Falls, Zimbabwe.

ICOMOS. 2008. *ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites*. Québec, Canada.

Jakob Iglhaut, Carlos Cabo, Stefano Puliti, Livia Piermattei, James O'Connor, and Jacqueline Rosette. 2019. Structure from Motion Photogrammetry in Forestry: a Review. *Current Forestry Reports 5*, 3, 155–168.

Katsushi Ikeuchi, Takeshi Oishi, Jun Takamatsu, et al. 2007. The great buddha project: Digitally archiving, restoring, and analyzing cultural heritage objects. *International Journal of Computer Vision 75*, 1, 189–208.

Giovanni Ioppolo. 1988. Il circo di Massenzio. La struttura architettonica. *La residenza imperiale di Massenzio. Villa, mausoleo, circo, Roma*.

Tony Jebara, Ali Azarbayejani, and Alex Pentland. 1999. 3D structure from 2D motion. *IEEE Signal processing magazine 16*, 3, 66–84.

Peter Jensen. 2018. Evaluating authenticity: the authenticity of 3D models in archaeological field documentation. In: McDonald Institute.

Todd D Jick. 1979. Mixing qualitative and quantitative methods: Triangulation in action. *Administrative science quarterly 24*, 4, 602–611.

Siân Jones, Stuart Jeffrey, Mhairi Maxwell, Alex Hale, and Cara Jones. 2018. 3D heritage visualisation and the negotiation of authenticity: the ACCORD project. *International journal of heritage studies 24*, 4, 333–353.

Timothy Hyungsoo Jung and M. Claudia tom Dieck. 2017. Augmented reality, virtual reality and 3D printing for the co-creation of value for the visitor experience at cultural heritage places. *Journal of Place Management and Development 10*, 2, 140–151.

Timothy Jung, M Claudia tom Dieck, Hyunae Lee, and Namho Chung. 2016. Effects of Virtual Reality and Augmented Reality on Visitor Experiences in Museum. *Information and Communication Technologies in Tourism 2016*, Springer International Publishing, 621–635.

Katerina Kabassi. 2017. Evaluating websites of museums: State of the art. *Journal of Cultural Heritage 24*, 184–196.

Jiyoung Kang. 2013. AR teleport: Digital reconstruction of historical and cultural-heritage sites for mobile phones via movement-based interactions. *Wireless personal communications 70*, 4, 1443–1462.

Victor Kaptelinin. 2011. Designing technological support for meaning making in museum learning: An activity-theoretical framework. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 1–10.

Vlasios Kasapakis, Damianos Gavalas, and Elena Dzardanova. 2018. 3D Modelling Through Photogrammetry in Cultural Heritage. In: N. Lee, ed., *Encyclopedia of Computer Graphics and Games*. Springer International Publishing, Cham, 1–4.

Akrivi Katifori, Manos Karvounis, Vassilis Kourtis, Sara Perry, Maria Roussou, and Yannis Ioanidis. 2018. Applying interactive storytelling in cultural heritage: opportunities, challenges and lessons learned. *International Conference on Interactive Digital Storytelling*, 603–612.

Dinesh Katre and Mandar Sarnaik. 2009. Identifying the cognitive needs of visitors and content selection parameters for designing the interactive kiosk software for museums. *IFIP Working Conference on Human Work Interaction Design*, 168–179.

Irene Katsouri, Aimilia Tzanavari, Kyriakos Herakleous, and Charalambos Poullis. 2015. Visualizing and assessing hypotheses for marine archaeology in a VR CAVE environment. *Journal on Computing and Cultural Heritage (JOCCH) 8*, 2, 1–18.

Suzanne Keene. 1996. Becoming digital. *Museum Management and Curatorship 15*, 3, 299–313.

Pramod Khambete and Uday Athavankar. 2010. Grounded Theory: An Effective Method for User Experience Design Research. *Design Thoughts*, 11–24.

Roshni Khunti. 2018. The problem with printing Palmyra: exploring the ethics of using 3D printing technology to reconstruct heritage. *Studies in digital heritage 2*, 1, 1–12.

Kangsoo Kim, Byung-Kuk Seo, Jae-Hyek Han, and Jong-Il Park. 2009. Augmented reality tour system for immersive experience of cultural heritage. *Proceedings of the 8th International Conference on Virtual Reality Continuum and its Applications in Industry*, 323–324.

Myung Ja Kim and C Michael Hall. 2019. A hedonic motivation model in virtual reality tourism: Comparing visitors and non-visitors. *International Journal of Information Management 46*, 236–249.

Brad King and Barry Lord. 2015. *The manual of museum learning*. Rowman \& Littlefield.

Barbara Kirshenblatt-Gimblett. 2004. Intangible heritage as metacultural production. *Museum international 56*, 1–2, 52–65.

Simon J Knell. 2013. *The shape of things to come: Museums in the technological landscape*. Routledge.

Aaron D Knochel, Wen-Hsia Hsiao, and Alyssa Pittenger. 2018. Touching to see: Tactile learning, assistive technologies, and 3-D printing. *Art Education 71*, 3, 7–13.

David Koller, Jennifer Trimble, Tina Najbjerg, Natasha Gelfand, and Marc Levoy. 2006. Fragments of the city: Stanford's digital forma urbis romae project. *Proceedings of the third Williams symposium on classical architecture*, 237–252.

Tsvi Kuflik, Judy Kay, and Bob Kummerfeld. 2010. Lifelong personalized museum experiences. *Proc. Pervasive User Modeling and Personalization (PUMP'10)*, 9–16.

Tsvi Kuflik, Oliviero Stock, Massimo Zancanaro, et al. 2011. A visitor's guide in an active museum: Presentations, communications, and reflection. *Journal on Computing and Cultural Heritage 3*, 3.

Steinar Kvale. 2008. Doing interviews. .

Bruno Latour and Adam Lowe. 2012. The Migration of the Aura, or How to Explore the Original through Its Facsimiles. In: T. Bartscherer, ed., *Switching codes : thinking through digital technology in the humanities and the arts*. University of Chicago Press, Chicago, 1–18.

Effie L.C. Law, Virpi Roto, Marc Hassenzahl, Arnold P.O.S. Vermeeren, and Joke Kort. 2009. Understanding, scoping and defining user experience: A survey approach. *Conference on Human Factors in Computing Systems - Proceedings* June 2014, 719–728.

Hyunae Lee, Timothy Hyungsoo Jung, M.Claudia tom Dieck, and Namho Chung. 2020. Experiencing immersive virtual reality in museums. *Information & Management 57*, 5, 103229.

Dirk Vom Lehn, Christian Heath, and Jon Hindmarsh. 2005. Rethinking interactivity: design for participation in museums and galleries. *Work, Interaction \& Technology Research Group, King's College London. Retrieved January 26*, 2006.

Mathias Lemmens. 2011. Photogrammetry: Geometric Data from Imagery. In: *Geo-information: Technologies, Applications and the Environment*. Springer Netherlands, Dordrecht, 123–151.

Marc a. Levoy. 1999. The Digital Michelangelo Project. *Computer Graphics Forum 18*, 3, xiii--xvi.

Marc Levoy, Kari Pulli, Brian Curless, et al. 2000. The Digital Michelangelo Project: 3D Scanning of Large Statues. *Proceedings of the 27th Annual Conference on Computer Graphics and Interactive Techniques*, ACM Press/Addison-Wesley Publishing Co., 131–144.

Antonia Liguori and Philippa Rappoport. 2018. Digital storytelling in cultural and heritage education : Reflecting on storytelling practices applied with the Smithsonian Learning Lab to enhance 21st-century learning. *International digital storytelling conference*.

Aleck C H Lin, Walter D Fernandez, and Shirley Gregor. 2012. Understanding web enjoyment experiences and informal learning: A study in a museum context. *Decision Support Systems 53*, 4, 846–858.

Anna Lindgren-Streicher and Christine A. Reich. 2007. Visitor usage of digital and physical artifacts in two museum programs. *Visitor Studies 10*, 2, 152–167.

Giorgio Lise. 1979. *Museo archeologico: raccolta egizia*. Electa.

Bingjian Liu, Fangjin Zhang, Xu Sun, and Adam Rushworth. 2020. Integration of Additive Manufacturing into Process Chain of Porcelain Preservation. *International Conference on Additive Manufacturing in Products and Applications*, 455–466.

Ying Liu. 2020. Evaluating visitor experience of digital interpretation and presentation technologies at cultural heritage sites: a case study of the old town, Zuoying. *Built Heritage 4*, 1.

A Lowe. 2020. *The Aura in the Age of Digital Materiality: Rethinking Preservation in the Shadow of an Uncertain Future*. Factvm Fovndation.

David Lowe. 1999. Object Recognition from local Scale-Invariant Features. *IEEE International Conference on Computer Vision*, 1150–1157.

David G Lowe. 2004. Distinctive Image Features from Scale-Invariant Keypoints. *International*

Journal of Computer Vision 60, 2, 91–110.

Livio De Luca. 2020. Towards the Semantic-Aware 3D Digitisation of Architectural Heritage: The "Notre-Dame de Paris" Digital Twin Project. *Proceedings of the 2nd Workshop on Structuring and Understanding of Multimedia HeritAge Contents*, Association for Computing Machinery, 3–4.

T Luhmann, S Robson, SA Kyle, and IA Harley. 2006. *Close Range Photogrammetry: Principles, Techniques and Applications*. Whittles Publishing, Dunbeath, Caithness.

Thomas. Luhmann, Stuart Robson, Stephen Kyle, and Jan Boehm, eds. 2014. *Close Range Photogrammetry : 3D Imaging Techniques*. De Gruyter, Berlin.

Thomas Luhmann. 2010. Close range photogrammetry for industrial applications. *ISPRS Journal of Photogrammetry and Remote Sensing 65*, 558–569.

Bernadette Lynch. 2013. Reflective debate, radical transparency and trust in the museum. *Museum Management and Curatorship 28*, 1, 1–13.

George F MacDonald and Stephen Alsford. 1991. The museum as information utility. *Museum Management and Curatorship 10*, 3, 305–311.

Lindsay MacDonald. 2006. *Digital heritage*. Routledge.

Sharon Macdonald, Helen Rees Leahy, Andrea Witcomb, et al. 2015. *The International Handbooks of Museum Studies*. Wiley-Blackwell.

Jacob B Madsen and Claus B Madsen. 2015. Handheld visual representation of a castle chapel ruin. *Journal on Computing and Cultural Heritage (JOCCH) 9*, 1, 1–18.

Umair Shafqat Malik and Gabriele Guidi. 2018. Massive 3D digitization of sculptures: Methodological approaches for improving efficiency. *IOP Conference Series: Materials Science and Engineering 364*, 1.

Umair Shafqat Malik, Liselore N M Tissen, and Arnold P O S Vermeeren. 2021. 3D Reproductions of Cultural Heritage Artefacts : Evaluation of significance and experience. *Studies in Digital Heritage 5*, 1, 1–29.

André Malraux. 1967. Museum Without Walls. Translated From the French by Stuart Gilbert and Francis Price. .

Guido Achille Mansuelli. 1958. *Galleria degli Uffizi. Le sculture.* Istituto poligrafico dello Stato, Libreria dello Stato, Rome.

Janet Marstine. 2013. Situated revelations: radical transparency in the museum. *New directions in museum Ethics*, 1–23.

Jochen Martin and Christian Trummer. 2005. Personalized multimedia information system for museums and exhibitions. *International Conference on Intelligent Technologies for Interactive Entertainment*, 332–335.

Fabio Marton, Marcos Balsa Rodriguez, Fabio Bettio, Marco Agus, Alberto Jaspe Villanueva, and Enrico Gobbetti. 2014. IsoCam: Interactive visual exploration of massive cultural heritage models on large projection setups. *Journal on Computing and Cultural Heritage (JOCCH) 7*, 2, 1–24.

Paul F. Marty, W. Boyd Rayward, and Michael B. Twidale. 2003. Museum informatics. *Annual Review of Information Science and Technology 37*, January 2005, 259–294.

Paul F. Marty and Katherine Burton Jones. 2008. *Museum Informatics: People, Information, and Technology in Museums*. .

Herbert D G Maschner, Corey D Schou, and Jonnathan Holmes. 2013. Virtualization and the democratization of science: 3D technologies revolutionize museum research and access. *2013 Digital Heritage International Congress (DigitalHeritage)*, 265–271.

Marco Mason. 2015. Prototyping practices supporting interdisciplinary collaboration in digital media design for museums. *Museum Management and Curatorship 30*, 5, 394–426.

Marco Mason. 2020. The Elements of Visitor Experience in Post-Digital Museum Design. *Participatory Design: Principles and Practices 14*, 1, 1–14.

Philipp Mayring. 2015. Qualitative content analysis: Theoretical background and procedures. In: *Approaches to qualitative research in mathematics education*. Springer, 365–380.

Andrew McClellan. 2008. *The art museum from Boullée to Bilbao*. Univ of California Press.

Melora McDermott. 1988. Through their eyes: What novices value in art experiences. *Annual Meeting Sourcebook. Washington, DC: American Association of Museums*, 135–162.

Melora McDermott. 1990. Motivation and Information Needs of Art Museum Visitors. A Cluster Analytic Study. *ILVS REVIEW 1*, 2, 21.

Andrew Mcintyre. 2014. *The Spectrum of Audience Engagement: A relationship policy matrix*. .

Kathleen McLean. 1999. Museum exhibitions and the dynamics of dialogue. *Daedalus 128*, 3, 83–107.

Luisa Menano, Patrícia Fidalgo, Ieda M. Santos, and Joan Thormann. 2019. Integration of 3D Printing in Art Education: A Multidisciplinary Approach. *Computers in the Schools 36*, 3, 222–236.

J D Meneely, B J Smith, Joanne Curran, and Alastair Ruffell. 2009. Developing a "non-destructive scientific toolkit" to monitor monuments and sites. *Proceedings of ICOMOS Scientific Symposium (Changing World, Changing Views of Heritage: the Impact of Global Change on Cultural Heritage--Technological Change)*.

Fabio Menna, Panagiotis Agrafiotis, and Andreas Georgopoulos. 2018. State of the art and applications in archaeological underwater 3D recording and mapping. *Journal of Cultural Heritage 33*, 231–248.

LUCA Miatello. 2018. Examining texts and decoration of Peftjauauiaset's coffins in Milan. *Égypte Nilotique et Méditerranéenne 11*, 41–133.

Laura Loredana Micoli, Giandomenico Caruso, and Gabriele Guidi. 2020. Design of digital interaction for complex museum collections. *Multimodal Technologies and Interaction 4*, 2, 1–20.

Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and telepresence technologies*, 282–292.

Michela Mortara and Chiara Catalano. 2018. 3D Virtual environments as effective learning contexts for cultural heritage. *Italian Journal of Educational Technology 26*, 2, 5–21.

Theano Moussouri and George Roussos. 2015. Conducting visitor studies using smartphone-based location sensing. *Journal on Computing and Cultural Heritage 8*, 3, 1–16.

Sander Münster. 2019. Digital heritage as a scholarly field—topics, researchers, and perspectives from a bibliometric point of view. *Journal on Computing and Cultural Heritage (JOCCH) 12*, 3, 1–27.

Museum Boijmans. 2009. Sgraffito in 3D. *Museum website*. https://www.boijmans.nl/en/exhibitions/sgraffito-in-3d.

Henri Neuendorf. 2018. The Uffizi Gallery's Treasures Are Now Online—See 5 Masterpieces in New Eye-Popping 3D Detail. *Artnet News*. https://news.artnet.com/art-world/indiana-university-uffizi-gallery-1332494.

Moritz Neumüller, Andreas Reichinger, Florian Rist, and Christian Kern. 2014. 3D printing for cultural heritage: Preservation, accessibility, research and education. In: *3D Research Challenges in Cultural Heritage*. Springer, 119–134.

Wenjian Ni, Guoqing Sun, Yong Pang, et al. 2018. Mapping Three-Dimensional Structures of Forest Canopy Using UAV Stereo Imagery: Evaluating Impacts of Forward Overlaps and Image Resolutions With LiDAR Data as Reference. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 11*, 10, 3578–3589.

Franco Niccolucci and Sorin Hermon. 2008. *EPOCH - Final Plan for Use and Dissemination of the Knowledge*. Prato, Italy.

Reinhard Oppermann and Marcus Specht. 2000. A context-sensitive nomadic exhibition guide. *International Symposium on Handheld and Ubiquitous Computing*, 127–142.

Jan Packer and Roy Ballantyne. 2002. Motivational Factors and the Visitor Experience: A Comparison of Three Sites. *Curator 45*, 3, 183–198.

Jan Packer and Roy Ballantyne. 2016. Conceptualizing the Visitor Experience: A Review of Literature and Development of a Multifaceted Model. *Visitor Studies 19*, 2, 128–143.

Gianpaolo Palma, Paolo Pingi, Eliana Siotto, Roberto Bellucci, Gabriele Guidi, and Roberto Scopigno. 2019. Deformation analysis of Leonardo da Vinci's "Adorazione dei Magi" through temporal unrelated 3D digitization. *Journal of Cultural Heritage 38*, 174–185.

Ioanna Papadimitriou, Vassilis Komis, Nikolaos Tselios, and Nikolaos Avouris. 2006. Designing PDA mediated educational activities for a museum visit. *Proceedings of Cognition and Exploratory Learning in Digital Age (CELDA 2006)*.

Ross Parry. 2013a. The End of the Beginning: Normativity in the Postdigital Museum. *Museum Worlds: Advances in Research 1*, 1, 24–39.

Ross Parry. 2013b. *Museums in a digital age*. Routledge.

Fabio Paternò and Cristiano Mancini. 2000. Effective levels of adaptation to different types of users in interactive museum systems. *Journal of the American Society for Information Science 51*, 1, 5–13.

Daniela Petrelli. 2019. Making virtual reconstructions part of the visit: An exploratory study. *Digital Applications in Archaeology and Cultural Heritage 15*, February, e00123.

Daniela Petrelli and Elena Not. 2005. User-centred design of flexible hypermedia for a mobile guide: Reflections on the hyperAudio experience. *User Modelling and User-Adapted Interaction 15*, 3–4, 303–338.

Daniela Petrelli, Elena Not, Areti Damala, Dick van Dijk, and Monika Lechner. 2014. meSch – Material encounters with digital cultural Heritage. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 8740*, 536–545.

Fabio Pianesi, Ilenia Graziola, Massimo Zancanaro, and Dina Goren-Bar. 2009. The motivational and control structure underlying the acceptance of adaptive museum guides - an empirical study. *Interacting with Computers 21*, 3, 186–200.

Massimiliano Pieraccini, Gabriele Guidi, and Carlo Atzeni. 2001. 3D digitizing of cultural heritage. *Journal of Cultural Heritage 2*, 1, 63–70.

Roberto Pierdicca, Emanuele Frontoni, Primo Zingaretti, Eva Savina Malinverni, Francesca Colosi, and Roberto Orazi. 2015a. Making visible the invisible. augmented reality visualization for 3D reconstructions of archaeological sites. *International Conference on Augmented and Virtual Reality*, 25–37.

Roberto Pierdicca, Emanuele Frontoni, Primo Zingaretti, Mirco Sturari, Paolo Clini, and Ramona Quattrini. 2015b. Advanced interaction with paintings by augmented reality and high resolution visualization: a real case exhibition. *International Conference on Augmented and Virtual Reality*, 38–50.

Eva Pietroni, Alfonsina Pagano, and Bruno Fanini. 2018. UX Designer and Software Developer at the Mirror: Assessing Sensory Immersion and Emotional Involvement in Virtual Museums. *Studies in Digital Heritage 2*, 1, 13–41.

Geraldine Pinch. 2004. *Egyptian Mythology: A Guide to the Gods, Goddesses, and Traditions of ancient Egypt*. Oxford University Press.

Antonella Poce, Maria Rosaria Re, Mara Valente, and Carlo De Medio. 2021. Using 3D Reproductions of Archaeological Objects in Museum Education Context. A Learning Experience within an Etruscan Musical Collection. *img journal* 4, 242–261.

Marc Pollefeys, Maarten Vergauwen, and Luc Van Gool. 2000. Automatic 3D modeling from image sequences. *International Archives of Photogrammetry and Remote Sensing 33*, B5/2; PART 5, 619–626.

F. Ponchio, M. Callieri, M. Dellepiane, and R. Scopigno. 2019. Effective Annotations Over 3D Models. *Computer Graphics Forum 00*, 00, 1–17.

Cristina Portalés, José L. Lerma, and Carmen Pérez. 2009. Photogrammetry and augmented reality for cultural heritage applications. *Photogrammetric Record 24*, 128, 316–331.

Elisabetta Povoledo. 2016. Uffizi, With Indiana University, Will Digitize Ancient Sculptures. *The New York Times*. https://www.nytimes.com/2016/05/27/arts/design/uffizi-with-indiana-university-will-digitize-ancient-sculptures.html.

N Proctor and C Tellis. 2003. The State of the Art in Museum Handhelds in Museums and the Web. .

George E Raptis, Christos Fidas, Christina Katsini, and Nikolaos Avouris. 2019. A cognition-centered personalization framework for cultural-heritage content. *User Modeling and User-Adapted Interaction*.

Donald B Redford. 2005. *The Oxford encyclopedia of ancient Egypt*. Oxford University Press.

Andreas Reichinger, Stefan Maierhofer, and Werner Purgathofer. 2011. High-quality tactile paintings. *Journal on Computing and Cultural Heritage (JOCCH) 4*, 2, 1–13.

Fabio Remondino. 2011. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sensing 3*, 6, 1104–1138.

Eva M Reussner. 2003. Strategic management for visitor-oriented museums: A change of focus. *The International Journal of Cultural Policy 9*, 1, 95–108.

Heather Richards-Rissetto, Jim Robertsson, Jennifer von Schwerin, Giorgio Agugiaro, Fabio Remondino, and Gabrio Girardi. 2014. Geospatial Virtual Heritage: a gesture-based 3D GIS to engage the public with Ancient Maya Archaeology. In: *Archaeology in the Digital Era*. Amsterdam University Press, 118–130.

Brett Ridel, Patrick Reuter, Jeremy Laviole, Nicolas Mellado, Nadine Couture, and Xavier Granier. 2014. The revealing flashlight: Interactive spatial augmented reality for detail exploration of cultural heritage artifacts. *Journal on Computing and Cultural Heritage (JOCCH) 7*, 2, 1–18.

Rijks Museum. 2020. Experience the Night Watch. *Museum website*. https://beleefdenachtwacht.nl/en.

Mario Mirabella Roberti. 1984. *Milano romana*. Rusconi: Sant'Arcangelo di Romagna.

Umberto Roberto. 2018. L'identità tetrarchica di Milano e l'Italia tardoantica. *Studia Ambrosiana 11*, 25–54.

Stuart Robson, Sally MacDonald, Graeme Were, and Mona Hess. 2012. 3D recording and museums. In: C. Warwick, M. Terras and J. Hyhan, eds., *Digital Humanities in Practice*. Facet Publishing, London, 91–115.

S. Tonette Rocco and S. Maria Plakhotnik. 2009. Literature reviews, conceptual frameworks, and theoretical frameworks: Terms, functions, and distinctions. *Human Resource Development Review 8*, 1, 120–130.

Kerry Rodden. 2014. Applying a sunburst visualization to summarize user navigation sequences. *IEEE Computer Graphics and Applications 34*, 5, 36–40.

Eleanor Jo Rodger, Corinne Jörgensen, and George D'Elia. 2005. Partnerships and collaboration among public libraries, public broadcast media, and museums: Current context and future potential. *The Library Quarterly 75*, 1, 42–66.

Pablo Rodríguez-Gonzálvez, Angel Luis Muñoz-Nieto, Susana DelPozo, et al. 2017. 4D reconstruction and visualization of cultural heritage: Analyzing our legacy through time. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 42*, 2W3, 609–616.

Yvonne Rogers and Henk Muller. 2006. A framework for designing sensor-based interactions to promote exploration and reflection in play. *International Journal of Human Computer Studies 64*, 1, 1–14.

Emilio Rossi and Paola Barcarolo. 2019. Use of Digital Modeling and 3D Printing for the Inclusive Valorization of Cultural Heritage. *Advances in Manufacturing, Production Management and Process Control*, Springer International Publishing, 257–269.

Jay Rounds. 1999. Meaning making: A new paradigm for museum exhibits. *Exhibitionist 18*, 2, 5–8.

Maria Roussou. 2001. The Interplay between Form , Story , and History : The Use of Narrative in Cultural and Educational Virtual Reality. *International Conference on Virtual Storytelling*, Springer-Verlag, 181–190.

Maria Roussou and Akrivi Katifori. 2018. Flow, staging, wayfinding, personalization: Evaluating user experience with mobile museum narratives. *Multimodal Technologies and Interaction 2*, 2.

Tuukka Ruotsalo, Eetu Mäkelä, Tomi Kauppinen, et al. 2009. Smartmuseum: Personalized Context-aware Access to Digital Cultural Heritage. *Proceedings of the International Conferences on Digital Libraries and the Semantic Web 2009 (ICSD2009)* June 2014.

Franz Russo. 2018. Uffizi Digitization Project, il patrimonio della Gallerie degli Uffizi in 3D e realtà virtuale. https://www.franzrusso.it/innovation/uffizi-digitization-project-il-patrimonio-della-gallerie-degli-uffizi-in-3d-realta-virtuale/.

Furio Sacchi and Maria Pia Rossignani. 2012. Perché Milano? Il destino di una città. .

Paolo Salonia, Tommaso Leti Messina, Andrea Marcolongo, and Lorenzo Appolonia. 2011. Photo scanner 3D survey for monitoring historical monuments. The case history of Porta Praetoria in Aosta. *Geoinformatics FCE CTU 6*, 314–322.

Pedro Santos, Martin Ritz, Reimar Tausch, et al. 2014. CultLab3D: On the verge of 3D mass digitization. *Proceedings of the Eurographics Workshop on Graphics and Cultural Heritage*, 65–73.

Foy Scalf and Kevin Bryce Lowry. 2017. *Book of the dead: becoming God in ancient Egypt*. The Oriental Institute of the University of Chicago.

Christopher Schwartz, Michael Weinmann, Roland Ruiters, and Reinhard Klein. 2011. Integrated High-Quality Acquisition of Geometry and Appearance for Cultural Heritage. *VAST*, 25–32.

Werner Schweibenz. 1998. The" Virtual Museum": New Perspectives For Museums to Present Objects and Information Using the Internet as a Knowledge Base and Communication System. *International Symposium of Information Science 34*, 185–200.

Roberto Scopigno, Paolo Cignoni, Marco Callieri, et al. 2003. Using optically scanned 3D data in the restoration of Michelangelo's David. *Optical metrology for arts and multimedia*, 44–53.

Roberto Scopigno, Paolo Cignoni, Nico Pietroni, Marco Callieri, and Matteo Dellepiane. 2017. Digital fabrication techniques for cultural heritage: A survey. *Computer Graphics Forum*, 6–21.

David A Scott. 2016. *Art: authenticity, restoration, forgery*. ISD LLC.

Jeffrey Shaw. 2016. 300 Years of Hakka Kung Fu: Digital vision of its legacy and future. *300 Years* *of Hakka Kung Fu: Digital Vision of its Legacy and Future*.

Yukihiko Shigesada, Noboru Koshizuka, and Ken Sakamura. 2003. A Kiosk WWW browser for digital museums. *Systems and Computers in Japan 34*, 59–70.

Lois H. Silverman. 1995. Visitor Meaning-Making in Museums for a New Age. *Curator: The Museum Journal 38*, 3, 161–170.

Nina Simon. 2010. *The participatory museum*. Museum 2.0.

Nina Simon. 2016. *The art of relevance*. Museum 2.0.

Mette Skov and Peter Ingwersen. 2014. Library & Information Science Research Museum Web search behavior of special interest visitors. *Library and Information Science Research 36*, 2, 91–98.

Smithsonian's Digitization Program Office. 2009. Smithsonian 3D digitization. *Smithsonian Institution*. https://3d.si.edu.

Ludovico Solima. 2008. Visitatore, cliente, utilizzatore : nuovi profili di domanda museale e nuove traiettorie di ricerca. In: A. Bollo, ed., *I pubblici dei musei. Conoscenza e politiche*. Franco Angeli, Milano, 65–76.

Filippo Stanco, Davide Tanasi, Dario Allegra, Filippo Luigi Maria Milotta, Gioconda Lamagna, and Giuseppina Monterosso. 2017. Virtual anastylosis of Greek sculpture as museum policy for public outreach and cognitive accessibility. *Journal of Electronic Imaging 26*, 1, 1–12.

John Stevenson. 1991. The long-term impact of interactive exhibits. *International Journal of Science Education 13*, 5, 521–531.

Harry M Stewart. 1995. *Egyptian shabtis*. Shire, Princes Risborough.

Oliviero Stock, Massimo Zancanaro, Paolo Busetta, et al. 2007. Adaptive, intelligent presentation of information for the museum visitor in PEACH. *User Modeling and User-Adapted Interaction 17*, 3, 257–304.

Adrian Stoica, Georgios Fiotakis, J Simarro Cabrera, H Muñoz Frutos, Nikolaos Avouris, and Yannis Dimitriadis. 2005. Usability evaluation of handheld devices: A case study for a museum application. *Proceedings PCI 2005*.

Robert Strohmaier, Gerhard Sprung, Alexander Nischelwitzer, and Sandra Schadenbauer. 2015. Using visitor-flow visualization to improve visitor experience in museums and exhibitions. *MW2015: Museums and the Web 2015*, 1–6.

S Shyam Sundar, Eun Go, Hyang-Sook Kim, and Bo Zhang. 2015. Communicating art, virtually! Psychological effects of technological affordances in a virtual museum. *International Journal of Human-Computer Interaction 31*, 6, 385–401.

Silvia Sussmann and Hugo Vanhegan. 2000. Virtual reality and the tourism product substitution or complement? .

Stella Sylaiou, Katerina Mania, Ioannis Paliokas, Laia Pujol-Tost, Vassilis Killintzis, and Fotis Liarokapis. 2017. Exploring the educational impact of diverse technologies in online virtual museums. *International Journal of Arts and Technology 10*, 1, 58–84.

Iwona Szmelter. 2013. New values of cultural heritage and the need for a new paradigm regarding its care. *CeROArt. Conservation, exposition, Restauration d'Objets d'Art*.

David Tanasi, Stephan Hassam, and Kaitlyn Kingsland. 2018. Virtual karam collection: 3D digital imaging and 3D printing for public outreach in archaeology. .

L Taşçi. 2015. Deformation monitoring in steel arch bridges through close-range photogrammetry and the finite element method. *Experimental Techniques 39*, 3, 3–10.

J Taylor, G Forester, F Livingstone, and R Baribeau. 1996. AMUSE: 3-D Colour Imaging, Remote Access and Display. *Electronic Imaging and the Visual Arts, EVA 96*, 1–9.

Chris Tellis. 2004. Multimedia handhelds: One device, many audiences. *Museums and the Web*, 367–383.

Ricardo Tesoriero, Mar\'\ia Dolores Lozano, José A Gallud, and Victor M Ruiz Penichet. 2007. Evaluating the Users' Experience of a PDA-based Software Applied in Art Museums. *WEBIST (2)*, 351–358.

Beau Tippetts, Dah Jye Lee, Kirt Lillywhite, and James Archibald. 2016. Review of stereo vision algorithms and their suitability for resource-limited systems. *Journal of Real-Time Image Processing 11*, 1, 5–25.

L N M Tissen. 2020. Authenticity vs 3D reproduction: Never the twain shall meet? *Arts in Society. Academic Rhapsodies*, Leiden University Centre for the Arts in Society, 21–40.

Eran Toch, Yang Wang, and Lorrie Faith Cranor. 2012. Personalization and privacy: a survey of privacy risks and remedies in personalization-based systems. *User Modeling and User-Adapted Interaction 22*, 1–2, 203–220.

P H S Torr and A Zisserman. 2000. MLESAC: A New Robust Estimator with Application to Estimating Image Geometry. *Computer Vision and Image Understanding 78*, 1, 138–156.

John Toylor, J. Angelo Beraldin, Guy Godin, et al. 2003. NRC 3D imaging technology for museum and heritage applications. *Journal of Visualization and Computer Animation 14*, 3, 121–138.

Hannah Turner, Gabby Resch, Daniel Southwick, Rhonda McEwen, Adam K Dubé, and Isaac Record. 2017. Using 3D printing to enhance understanding and engagement with young audiences: lessons from workshops in a museum. *Curator: The Museum Journal 60*, 3, 311–333.

UCL. 2018. 3D Petrie Museum. https://www.ucl.ac.uk/3dpetriemuseum/.

UNESCO. 2009. *Charter on the Preservation of the Digital Heritage*. .

UNESCO, ICOMOS, and ICCROM. 1994. *the Nara Document on Authenticity*. .

Tamas Varady, Ralph R Martin, and Jordan Cox. 1997. Reverse engineering of geometric models—an introduction. *Computer-aided design 29*, 4, 255–268.

Giasemi Vavoula and Marco Mason. 2017. Digital exhibition design: boundary crossing, Intermediary Design Deliverables and processes of consent. *Museum Management and Curatorship 32*, 3, 251–271.

Giasemi Vavoula and Mike Sharples. 2009. Meeting the Challenges in Evaluating Mobile Learning:

A 3-Level Evaluation Framework. *International Journal of Mobile and Blended Learning (IJMBL) 1*, 2, 54–75.

Arnold P.O.S. Vermeeren, Licia Calvi, Raffaella Trocchianesi, et al. 2018. Future Museum Experience Design: Crowds, Ecosystems and Novel Technologies. In: *Springer Series on Cultural Computing*. 1–16.

Chiara Villa and Christina Jacobsen. 2019. The Application of Photogrammetry for Forensic 3D Recording of Crime Scenes, Evidence and People. In: G.N. Rutty, ed., *Essentials of Autopsy Practice: Reviews, Updates and Advances*. Springer International Publishing, Cham, 1–18.

Salvador Muñoz Viñas. 2002. Contemporary theory of conservation. *Studies in Conservation 47*, sup1, 25–34.

Virtual World Heritage Lab. 2019. The Uffizi Digitization Project. http://www.digitalsculpture.org/florence/.

Jasper Visser, Jim Richardson, Rick Lawrence, et al. 2013. Digital Engagement in Culture, Heritage and the Arts. 67.

Vassilios Vlahakis, John Karigiannis, Manolis Tsotros, et al. 2001. Archeoguide: first results of an augmented reality, mobile computing system in cultural heritage sites. *Virtual Reality, Archeology, and Cultural Heritage 9*, 10.1145, 584993–585015.

Peter Waldhäusl and Clifford L Ogleby. 1994. 3×3-rules for simple photogrammetric documentation of architecture. *ISPRS Commission V Symposium. Close range techniques and machine vision*, ISPRS, 426–429.

Peter Waldhäusl, Clifford L Ogleby, J L Lerma, and Andreas Georgopolus. 2013. 3 x 3 rules for simple photogrammetric documentation of architecture. Updated version. .

Stephan Weibelzahl. 2005. Problems and pitfalls in the evaluation of adaptive systems. In: *Adaptable and adaptive hypermedia systems*. IGI Global, 285–299.

Stephan Weibelzahl, Alexandros Paramythis, and Judith Masthoff. 2020. Evaluation of adaptive systems. *Proceedings of the 28th ACM Conference on User Modeling, Adaptation and personalization*, 394–395.

Susie Wilkening and James Chung. 2009. *Life stages of the museum visitor: Building engagement over a lifetime*. AAM Press Washington, DC.

Paul F Wilson, Susan Griffiths, Ellis Williams, M Paul Smith, and Mark A Williams. 2020. Designing 3-D prints for blind and partially sighted audiences in museums: exploring the needs of those living with sight loss. *Visitor Studies 23*, 2, 120–140.

Paul F Wilson, Janet Stott, Jason M Warnett, Alex Attridge, M Paul Smith, and Mark A Williams. 2017. Evaluation of touchable 3D-printed replicas in museums. *Curator: The Museum Journal 60*, 4, 445–465.

Paul F Wilson, Janet Stott, Jason M Warnett, Alex Attridge, M Paul Smith, and Mark A Williams. 2018. Museum visitor preference for the physical properties of 3D printed replicas. *Journal of Cultural Heritage 32*, 176–185.

Christine M. van Winkle and John H. Falk. 2015. Personal meaning mapping at festivals: A useful tool for a challenging context. *Event Management 19*, 1, 143–150.

Paul R Wolf and Bon A Dewitt. 2000. *Elements of photogrammetry : with applications in GIS*. McGraw-Hill, Boston; London.

Allison Woodruff, Paul M Aoki, Rebecca E Grinter, Amy Hurst, Margaret H Szymanski, and James D Thornton. 2002. Eavesdropping on electronic guidebooks: Observing learning resources in shared listening environments. *arXiv preprint cs/0205054*.

Jie Xu, Lieyun Ding, and Peter E D Love. 2017. Digital reproduction of historical building ornamental components: From 3D scanning to 3D printing. *Automation in Construction 76*, 85–96.

Yan Ke and R. Sukthankar. 2004. PCA-SIFT: a more distinctive representation for local image descriptors. *Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2004. CVPR 2004. 2*, 506–513.

Yun Yang. 2015. 3D printing technology in the application of ceramic restoration and replication. *Sciences of Conservation and Archaeology 27*, 2, 110–113.

Koji Yatani, Mayumi Onuma, Masanori Sugimoto, and Fusako Kusunoki. 2004. Musex: A system for supporting children's collaborative learning in a museum with PDAs. *Systems and Computers in Japan 35*, 14, 54–63.

Yuhe Zhang, Kang Li, Xiaoxue Chen, Shunli Zhang, and Guohua Geng. 2018. A multi feature fusion method for reassembly of 3D cultural heritage artifacts. *Journal of Cultural Heritage 33*, 191–200.

J M Zheng, K W Chan, and I Gibson. 1998. Virtual reality. *IEEE Potentials 17*, 2, 20–23.

Guoqing Zhou, Qing Wang, and Zhaolin Xiao. 2017. Robust outlier removal using penalized linear regression in multiview geometry. *Neurocomputing 267*, 455–465.

Jing Zhou, Xiuqing Fu, Leon Schumacher, and Jianfeng Zhou. 2018. Evaluating Geometric Measurement Accuracy Based on 3D Reconstruction of Automated Imagery in a Greenhouse. *Sensors 18*, 7, 2270.