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# A Generic Pipeline for Creating Immersive Experiences Towards Cultural Heritage Preservation, Dissemination, and Promotion

Master's thesis in Simulation and Visualization

Supervisor: Ricardo da Silva Torres

Co-supervisor: Arne Styve

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Department of ICT and Natural Sciences



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10. June 2022

# Abstract

New technologies, such as 3D reconstruction and eXtended Reality, are increasingly being used in the field of Cultural Heritage to create immersive Virtual Heritage experiences. A literature review on these technologies, conducted in the context of this work, indicate that they have been applied in the field to create 3D models of objects and display them in immersive experiences for the purposes of preservation, dissemination, and promotion. However, existing pipelines that outline a workflow to create these experiences are often highly specialized and require expert knowledge of these technologies. Therefore, this thesis introduces a generic pipeline to provide guidance on how to create immersive experiences regardless of technique, tools, or equipment. The pipeline is validated by developing a mobile AR experience using the iPhone 13 Pro, commercial iOS applications, and Spark AR Studio, which allows interior and exterior exploration of a Cultural Heritage building in Ålesund, Norway. This approach shows that non-experts can develop such experiences using familiar equipment and simple tools, yet the selected building was not the ideal target of this methodology due to issues related to the modelling of the sod roof and file size constraints on the AR platform. These kinds of experiences could be leveraged in the Metaverse to generate funds for museums, increase peoples exposure to Cultural Heritage, and give lost artifacts a new virtual existence.

# Sammendrag

Nye teknologier som 3D rekonstruksjon og utvidet virkelighet blir ofte brukt til å lage virtuelle opplevelser innen kulturarv. En litteratur studie gjort i denne master oppgaven på disse teknologiene indikerer at de blir brukt til å lage virtuelle kopier av kulturelle objekter og viser dem gjennom interaktive virtuelle opplevelser for å bevare, formidle og promotere kulturarv. Produseringen av slike opplevelser krever en metodikk som forklarer stegene som må utføres for å lage dem, men disse er ofte spesialiserte og krever ekspertise innen de forskjellige teknologiene. Av denne grunn foreslås en generisk arbeidsflyt som kan utføres uansett hvilke teknikker, verktøy, eller utstyr som ønskes. Denne arbeidsflyten valideres gjennom en casestudie, hvor en mobil Augmented Reality opplevelse blir utviklet ved bruk av iPhone 13 Pro, kommersielle applikasjoner funnet i App Store, og Spark AR Studio. Opplevelsen lar brukeren plassere, modifisere og utforske en virtuell kopi av en kulturell bygning funnet på Sunnmøre Museum i Ålesund. Denne tilnærmingen viser at man ikke trenger ekspertise innen disse teknologiene for å lage slike opplevelser men problemer med modellering av gress taket og begrensninger på filstørrelser i utviklingsverktøyet indikerer at den ikke er passende for lignende norske kulturelle bygninger. Slike opplevelser kan bli brukt i det kommende Metaverset til å generere inntekt for kultur institusjonene, øke eksponeringen av kulturarv og gi tapte kulturelle gjenstander et nytt virtuelt liv.

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This master's thesis, and the research work behind it, would not have been possible without the guidance and support of my supervisors, Prof. Arne Styve and Prof. Ricardo da Silva Torres. Your willingness to hear my ideas and encouragement in following my academic curiosity allowed me to shape the thesis in my own vision.

I would also like to thank Thorbjørn Akslen and the Sunnmøre museum for granting me access to your buildings and listening to my ideas. Your generosity helped me validate my work and gave me a great excuse to explore your beautiful museum.

This thesis was awarded the *Masterstipend innan kultur* (Master's Scholarship in Culture) from the Møre og Romsdal Municipality and was granted financial support. I would like to thank Mona Fluge, Heidi-Iren Wedlog Olsen, and the entire cultural department at Møre og Romsdal Municipality for selecting my thesis. This financial support allowed me to completely focus on the research work without having to worry about paying my ever increasing electrical bills.

This research work is a continuation of my specialization project, which was done in collaboration with Geirangerfjord World Heritage Foundation and the Twin Fjord [grant number #320627] project funded by the Research Council of Norway. I would therefore like to thank Katrin Blomvik Bakken and Dina Margrethe Aspen for introducing me to this interesting research topic, which was the catalyst for the thesis.



# Preface

This master's thesis is submitted as a part of the Master of Science degree in Simulation and Visualization at the Norwegian Institute of Science and Technology (NTNU) in Ålesund. This research work was carried out during the final semester (spring 2022) of the master program.

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# Acronyms

**AR** Augmented Reality. 3–7, 14, 17–19, 21, 22, 29, 31, 35, 39, 40, 43, 47, 50–52

**BIM** Building Information Modelling. 13

**CAVE** Cave Automatic Virtual Environment. 15

**CGI** Computer-Generated Imagery. 28

**CH** Cultural Heritage. 1–22, 24–26, 28–32, 35, 40, 45–47, 49–53

**GPU** Graphics Processing Unit. 38

**HBIM** Historic Building Information Modelling. 11, 13, 22, 27, 49, 51, 52

**HHD** Hand-Held Devices. 14, 15

**HMD** Head-Mounted-Display. 14, 15, 20

**IVHE** Immersive Virtual Heritage Experiences. 5, 24, 25, 27, 29, 31, 45, 46, 52

**LiDAR** Light Detection and Ranging. 10

**MR** Mixed Reality. 6, 7, 19–22, 29, 47, 52

**NURBS** Non-Uniform Reation B-Spline. 11–13, 27, 51

**SAR** Spatial AR. 14

**TLS** Terrestrial Laser Scanning. 10, 11, 22

**UAV** Unmanned Aerial Vehicle. 9, 22

**VH** Virtual Heritage. 1–4, 6–8, 24, 29, 30, 47, 52

**VR** Virtual Reality. 6, 7, 14–19, 21, 22, 29, 50

**XR** eXtended Reality. 1–7, 13–15, 20–22, 24, 49–51

# Chapter 1

## Introduction

This chapter provides an overview of the research topic by introducing the motivation, objective, methodology, and structure of the thesis.

### 1.1 Background and Motivation

Cultural Heritage (CH) is of special significance for each culture and much effort has been invested in the protection and dissemination of cultural objects and sites. Monuments, buildings, and other artifacts are often preserved from previous generations to educate the current generation about the history of their culture and how it has shaped their identities. Despite the efforts of CH institutions to promote these precious objects, interest in exploring them is decreasing, especially in younger generations [1].

To address this issue, research is being conducted on the potential of using new technologies in the field of CH. One of the most promising sets of technologies being explored are the so-called immersive technologies, which are used to extend our current perception of reality. The use of these technologies, also called eXtended Reality (XR), has been investigated in the context of CH for more than 20 years for the purposes of education, reconstruction, exhibition enhancement, and more [2]. XR can display virtual environments that are embedded with CH that can allow interaction, exploration, and gamification that were not possible before.

Such virtual CH environments are often called Virtual Heritage (VH) [3] and can display digitized copies of actual CH artifacts and landscapes that are modelled from their physical versions. The process of creating such virtual artifacts from real-world objects is often categorized as 3D reconstruction, which is related to the process of collecting three-dimensional data on the artifact and developing a 3D model that can be used for the purposes of visualization, interaction and more [4]. 3D reconstruction has also been investigated for its potential to aid in the preservation process CH [5]. As many CH artifacts are fragile and prone to natural disasters, weather, and general degeneration, having accurate 3D data and 3D models of the artifacts can help in the restoration process.

One potential beneficiary of this technology is the country of Norway, where a large percentage of CH buildings need restoration. 55% of them need some form of repair to



improve their condition to a maintenance level and the estimated cost of repairing these buildings totals approximately three billion NOK [6]. Due to worsening weather and a lack of funds, museums are already forced to make tough decisions on which buildings they want to keep in their collection [7]. Collecting 3D data for 3D models of these buildings could be crucial to preserve the CH they contain before they inevitably perish.

Giant companies, such as Meta,<sup>1</sup> have been developing a multi-user virtual world that merges with the physical world using immersive technologies. Many believe that this is the next evolution of the Internet, where all people will have a virtual existence and meet their friends in virtual spaces. Although it is still many years in the future and there is a need for several technological breakthroughs before it is ready, some of the fundamental building blocks are already in place [8].

The author researched a similar solution in the specialization project preceding the master's thesis. That project explored the possible use cases of XR for the Geirangerfjord World Heritage Foundation, a not-for-profit organization tasked with protecting, preserving and conveying the CH in the Geiranger region. One of the proposed use cases referred to exploring CH buildings using mobile Augmented Reality, and a proof-of-concept application was developed to test the validity of the solution. After receiving encouraging feedback from researchers and experts in the field, a decision was made to continue exploring this research topic. This thesis is a continuation of that work, further exploring how new technological developments can be used to preserve, disseminate and promote CH buildings.

## 1.2 Objectives and Research Questions

The objective of the conducted research is twofold and relates to a desire to explore and incentivize the use of new technologies, such as XR and 3D reconstruction, in the field of CH. The first objective is to explore the ways immersive VH experiences based on XR technologies can be beneficial. The recent developments of the technologies involved in the creation of such experiences have allowed more research and exposure within its use of CH. An overview of the techniques, methods, and equipment needed for these technologies as well as specific use cases in the field can give CH institutions inspiration to develop their own experiences. The second objective is to encourage the development of new immersive experiences in the field of CH. The prospect of using these new technologies may seem daunting to researchers and CH institutions alike, so there is a need to provide guidance regarding how they can be created.

To properly address the objectives of this work and seek to achieve them, research questions were articulated based on each:

**RQ<sub>1</sub>**: How can immersive experiences in eXtended Reality be leveraged to preserve, disseminate, and promote Cultural Heritage?

**RQ<sub>2</sub>**: How to design, implement, and validate a generic pipeline to create virtual Cultural Heritage content and present it in immersive experiences?

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<sup>1</sup><https://about.facebook.com/> (As of June 2022).

The first research question (**RQ<sub>1</sub>**) aims to explore the ways that immersive VH experiences accessed using XR technologies can help for several key aspects of CH: preservation, dissemination, and promotion. *Preservation* relates to the desire to protect and store the CH object itself and its related information and history. *Dissemination* concerns educating the public about CH by communicating its significance and history. *Promotion*, in turn, relates to the desire to increase CH exposure and encourage more visitors to interact with and benefit from it. This research question will be addressed by a review of the literature on the use of immersive experiences in CH, which will focus on three aspects: frameworks for creating such experiences, 3D reconstruction of artifacts, and immersive technologies used to display them. Moreover, the introduction of the Metaverse and its implications for the CH field with regard to these aspects will also be explored.

The process of creating such experiences requires a series of steps, often referred to as a pipeline. The second research question (**RQ<sub>2</sub>**) will explore if it is possible to create a generic pipeline to facilitate the process of getting from the 3D reconstruction of CH objects to displaying them in immersive experiences using XR. The *design* aspect refers to the formulation of the necessary steps in the pipeline, while *implementation* refers to the tools and techniques necessary to construct immersive experiences. The *validation* aspect, in turn, refers to the need to assess whether the proposed pipeline is sound and effective. This research question will be addressed by designing a generic pipeline to create immersive VH experiences in XR technologies, and a case study will be conducted to validate the effectiveness of such a pipeline in creating experiences. Moreover, an exploration of the implications that the Metaverse will pose as a destination for the created immersive experiences will be provided.

### 1.3 Contributions

One contribution of this work is the literature review conducted into the use of immersive experiences in the field of CH. Although other works have looked at the three aspects of immersive experiences separately; pipeline [9, 10], 3D reconstruction [4, 11], and immersive technologies [2, 12], this review combines them into an overview of all three aspects in the context of CH.

Another contribution is the proposal of a generic pipeline to create immersive experiences of CH. The pipeline synthesizes the necessary steps to create such experiences without linking them to a specific tool or technique. It aims to be nonspecific and suited for non-experts and can be used as a guideline for stakeholders, developers, and practitioners in the area.

The case study conducted in this thesis uses novel tools and technologies that have not been attempted before in the CH literature. An assessment of the effectiveness of using the iPhone 13 Pro and commercial applications available in the App Store for 3D reconstruction, as well as the potential to develop immersive experiences in Meta's AR platform Spark AR Studio,<sup>2</sup> is provided.

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<sup>2</sup><https://sparkar.facebook.com/ar-studio/> (As of June 2022).

A final contribution is the exploration of the impact of the Metaverse in the field of CH. To the author's knowledge, no other studies have investigated the possible impact of this new technological innovation to assess how CH institutions can use it and how they can benefit from this development.

## 1.4 Methodology

To address the research questions, the thesis is divided into four main parts: (1) literature review of the technologies involved in immersive VH experiences, (2) proposal of a generic pipeline to create such experiences, (3) a case study of this pipeline implemented for a CH building in Ålesund, Norway, and finally, (4) an overview of the possibilities of VH in the Metaverse.

The literature review was conducted using IEEE Xplore<sup>3</sup> and Google Scholar.<sup>4</sup> IEEE Xplore offers the highest quality scientific literature in engineering and technology, while Google Scholar provides the most popular and cited literature in these fields. An extensive search was conducted in these two literature search engines to find relevant literature exploring immersive experiences used in the context of CH. The initial search identified three main aspects to focus on within the field of CH: 3D reconstruction of objects, XR applications, and existing frameworks that combine the two preceding aspects. A more specific search was then conducted into each of these aspects, exploring the technologies, equipment, benefits, and challenges involved.

The proposed pipeline aims to provide a generic workflow of how to get from the acquisition of 3D data from CH artifacts and landscapes to displaying them in immersive experiences using XR technologies. It aims to be nonspecific to technical decisions, such as specific platforms, technology, equipment, or tools, rather offering a holistic view of the overlying steps that need to be conducted in order to complete the process. It was designed by analyzing the findings of the literature review and identifying the common steps needed to create immersive VH experiences, regardless of technical decisions.

A case study was also realized based on an implementation of the pipeline. The case study was conducted a CH building located at the Sunnmøre Museum in Ålesund, Norway with their permission. This thesis describes equipment, methods, and challenges related to the scanning, modelling, and presentation of that building. The building was scanned using an iPhone 13 Pro Max, through commercially available third-party applications in the App store, modelled with the open source computer graphics software Blender, and developed as a mobile Augmented Reality experience using Spark AR Studio.

Finally, an analysis of the possibilities for immersive VH experiences within the upcoming Metaverse is also included. This part will be based on the Meta Connect 2020 keynote, where Meta outline their vision for the Metaverse, to discuss how CH institutions can use this development to their advantage.

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<sup>3</sup><https://ieeexplore.ieee.org/Xplore/home.jsp> (As of June 2022).

<sup>4</sup><https://scholar.google.com/> (As of June 2022).

## 1.5 Thesis Structure

The rest of the thesis is structured as follows:

**Chapter 2 - Background Concepts and Related Work** describes the background concepts related to the thesis and provides a review of the literature that summarizes the related work found in the literature on immersive experiences in the context of CH.

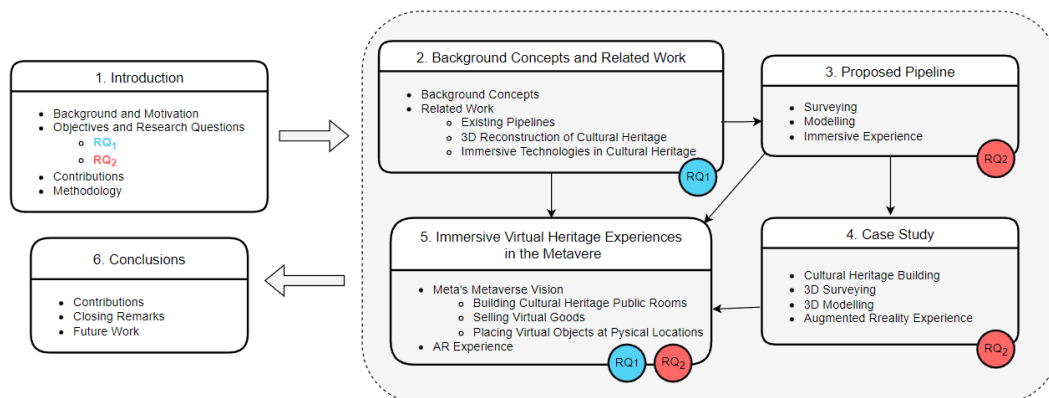
**Chapter 3 - Proposed pipeline** describes the proposed pipeline to create an Immersive Virtual Heritage Experiences (IVHE), outlining a workflow of the necessary steps needed to develop such experiences in XR.

**Chapter 4 - Case Study** describes the implementation of the proposed framework for a building at the Sunnmøre Museum in Ålesund. It outlines the development of a proof-of-concept mobile AR experience.

**Chapter 5 - Immersive Virtual Heritage Experiences in the Metaverse** discusses the impact that the Metaverse could have on immersive experiences of CH based on the vision described in *Meta Connect 2021*.

**Chapter 6 - Immersive Technology in Cultural Heritage** provides a discussion of the thesis' findings and contributions, attempting to answer the research questions posed. This chapter also outlines possible future work related to the thesis.

Figure 1.1 outlines the thesis chapters and their relationship to each other, also indicating their relation to the proposed research questions.



**Figure 1.1:** Thesis outline describing each chapters content, relationships and associated research questions.

## Chapter 2

# Background Concepts and Related Work

This chapter presents the background concepts on which the thesis is based and provides an overview of related work concerning existing pipelines, 3D reconstruction, and immersive technology applications in the context of Cultural Heritage.

### 2.1 Background Concepts

**Cultural Heritage (CH)** is a term that describes the legacy of tangible and intangible heritage assets inherited from previous generations of a group or society [13]. Not all the legacy passed down from previous generations is deemed as ‘heritage.’ In fact, it is a product of selection by society [13]. CH encompasses three different types: tangible culture (e.g., buildings, artifacts, monuments, landscapes, books, works of art, and more), intangible culture (e.g., traditions, language, folklore, and knowledge) and natural heritage (including biodiversity and culturally significant landscapes) [14].

**Virtual Heritage (VH)** is a term that describes virtual environments that are embedded in Cultural Heritage and represented through digital media [3]. It encompasses the digitization of CH landmarks, artifacts, and landscapes, exploring how new media and technologies can portray them to the public. VH is a mixture of cultural artifacts, such as historic buildings, sites, and monuments, with the technology of 3D visualization, animation, Virtual Reality, game engines, and more [15].

**eXtended Reality (XR)** is a term that encompasses all real-and-virtual environments and human-machine interactions generated by computers, where ‘X’ stands for a variable that can fit any spatial computing technology [16]. XR refers to all combined real-and-virtual environments and human-computer interactions generated by wearable technology [17]. In short, it is an umbrella term for technologies like Augmented Reality, Virtual Reality, and Mixed Reality.

**Virtual Reality (VR)** is a technology that allows interaction between the user and a computer-simulated environment, which can be a simulation of the real world or an imaginary world. In VR, people can have access to immersive, interactive experiences

in which they perceive a simulated environment using specialized equipment [18]. It allows users to visit and interact with a completely virtual environment that can be designed according to the objectives of the VR experience.

**Augmented Reality (AR)** is a technology that combines data from the physical world with virtual data. AR seeks to improve our perception of the physical world by superimposing virtual objects into the physical world to persuade the user that the virtual object is part of the real environment [19]. There are four types of AR: (1) marker-based AR, where one scans a QR code; (2) projection-based AR, where artificial light is projected onto real-world surfaces; (3) location-based AR, which is integrated with GPS for mapping directions; and finally, (4) superimposition-based AR, where a virtual artifact is superimposed into the real environment [17].

**Mixed Reality (MR)** is a technology that combines the capabilities of VR and AR. An MR system combines distinct VR and AR features that interact but are not tightly integrated, synchronizing the physical and virtual environments to align the virtual environment with the real world [20]. MR facilitates the interaction of virtual content with the real world [17].

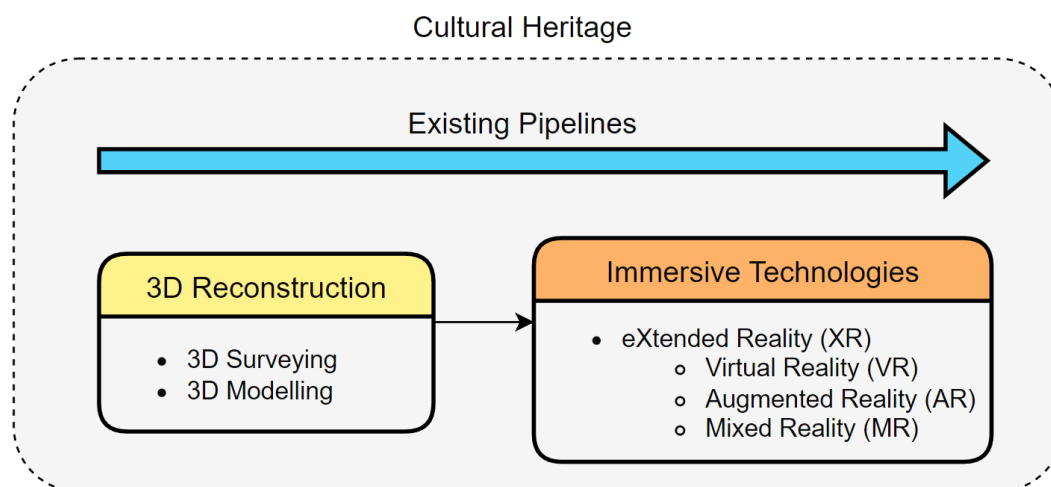
**Metaverse** is a term comprised of two words: Meta (Greek prefix meaning post, after or beyond) and universe. It describes a persistent and perpetual multi-user environment that merges the physical world with a virtual world [21]. The Metaverse can be defined as a virtual world in which multiple users from remote physical locations can interact in real time with each other for different purposes [22].

## 2.2 Related Work

This section provides a literature review on similar work related to the thesis. It focuses on three main aspects of immersive VH experiences: (1) 3D reconstruction, (2) immersive technologies, and finally, (3) existing pipelines. The literature was found using IEEE Xplore and Google Scholar, using base search strings, such as “cultural heritage,” “virtual heritage,” and “preservation.”

Section 2.2.1 is organized based on the pipeline proposed by Gomes et al. [4], which reviews the 3D reconstruction process in the context of CH. It condenses the four steps outlined in the paper into two main steps, *3D surveying* and *3D modelling*, where the main techniques are outlined for each. Additional papers were identified and used throughout the section using search strings such as “3D reconstruction,” “3D documentation,” “3D survey,” and “3D modelling” combined with the base strings.

Section 2.2.2 uses the comprehensive review published by Bekele et al. [2], which outlines the uses of the XR technologies in CH, as a starting point. However, the review only covers papers published before 2018 and a more current review is warranted as more research into the field has been conducted since then. This section compares the trends from before 2018 and the more recent research in the field, according to several aspects, such as application purpose and devices. An overview of the benefits and challenges posed for each of the XR technologies (VR, AR, and MR) is also provided. This search was conducted using search strings consisting of the base strings and terms such as “eXtended Reality,” “Virtual Reality,” “Augmented Reality,” and “Mixed Reality.”



**Figure 2.1:** Overview of the literature review topics and their relationships.

Finally, Section 2.2.3 describes the methodology of the existing pipelines proposed in the literature that combine 3D reconstruction and immersive technologies to create immersive VH experiences. The search was conducted by using search strings such as “workflow,” “pipeline,” and “framework” combined with base strings.

An overview of the three literature review topics and their relationship with each other can be seen in Figure 2.1.

### 2.2.1 3D Reconstruction of Cultural Heritage

The process of creating an accurate 3D model from a real-life object is called 3D reconstruction, which refers to the capture and reproduction of the shape and appearance of an arbitrary scene or object based on color and depth information [4]. A complete pipeline to 3D reconstruct CH objects can be divided into four major steps: Data acquisition, registration, mesh integration, and texture generation [4]. *Data acquisition* refers to the methodologies and equipment used to collect 3D data on the object. The *registration* step concerns aligning the collected range images or point clouds, while *mesh integration* refers to integrating the raw data into a single mesh without losing information or artifacts. *Texture generation*, in turn, refers to the addition of precise color data that improves the visual aspects of the 3D model by mapping a 2D image onto the 3D object.

In this section, these four steps are combined and condensed into two: *3D Surveying*, which combines data acquisition and registration, and *3D modelling*, which combines mesh integration and texture generation.

#### 3D Surveying

Reality-based 3D surveying is meant as the digital recording of existing scenes and objects for the purposes of 3D reconstructing them to create accurate 3D models [23].

Reality-based 3D surveying techniques use software and hardware to metrically survey reality as it is by means of range-data, images, or an integration of the two [11]. There are three main techniques for 3D surveying: image-based, range-based, and multi-sensor. Each of these methods recruit different sensors and techniques to create and document the shape and textures of the target object, which render them more useful for certain types of objects than others. The choice of technique is based on a number of aspects, including: required accuracy, location constraints, object dimensions, characteristics of the surface, team experience, budget, goal, purpose of collecting data, etc. [23].

### **Image-based surveying**

Image-based surveying refers to the use of images to reconstruct the shape of a given object [12], and requires a mathematical formulation to transform the 2D images into 3D information [11].

The most common technique for processing image data is photogrammetry [23]. Photogrammetry is the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena [24]. In simpler terms, it is a technique that turns photographs into 3D models. This technology has been used to gather 3D object information and texture information for a long time and because of the rapid advances in computing devices, photogrammetry can turn photos of buildings into complete 3D models with relative ease [5]. Photogrammetry is divided into two main categories: *terrestrial* and *aerial*. Terrestrial (ground) photogrammetry deals with photographic images taken from fixed positions on the ground, and determines the dimensions, position, and properties of the objects in the images [5]. The equipment used for this type of data is digital cameras. The camera should ideally be professional grade, like a digital single lens reflex camera, but due to the high quality of today's smartphone cameras, sufficiently accurate 3D models can also be developed from phone images [25]. Aerial photogrammetry deals with the interpretation and evaluation of images taken from the air and is mostly used for mapping larger territorial units and landscapes. Unmanned Aerial Vehicles (UAV), such as drones, are of particular interest for this purpose [23]. Image-based methods are generally preferred in cases of lost objects, buildings or monuments with regular geometric shapes, and smaller objects and projects that operate with low budgets [11]. Moreover, they are commonly used for geometric surfaces of architecture objects or precise terrain modelling [12].

Image-based reconstruction methods, like photogrammetry, are the most widely used for 3D documentation in CH due to their completeness, portability, costs, and flexibility [23]. This means that there are many examples of this approach being used in the context of CH. One example is the work of Banfi et al. [26], which recreated the Arco della Pace in Milan using both terrestrial and aerial photogrammetry by documenting it using a drone and digital camera. Photogrammetry was also used in the paper by Shih et al. [27]. Their work explored the creation 3D models of old cultural elements in the heritage site of Lukang and Taipei. Fandáková et al. [5] also employed photogrammetry to create a 3D virtual model of Kúnerad Castle in Slovakia.



### Range-based surveying

Range-based surveying refers to the use of optical range sensors to document a three-dimensional object in the form of unstructured point clouds. One such sensor is Light Detection and Ranging (LiDAR) which is a remote sensing technique that uses laser light in a radar fashion to collect surface points for environments or objects. LiDAR instruments send a pulse of laser energy and measure the round-trip between the sensor and the target. The round-trip time provides a distance between the two points that are converted into 3D coordinates of surface points [28]. The result of a LiDAR scan is a point cloud that represents a 3D image of the scanned target. LiDAR can also be divided into two categories: terrestrial and aerial. Based on the purpose of the data, the scanners used for these two types require varying specifications. The most important specifications are *range*, the maximum distance between the sensor and target, and *accuracy*, and the distance between the laser pulses [29]. Some of the main issues related to range-based documentation is the automated extraction of features and the generation of structured 3D data from the points [23]. Moreover, range-based 3D models contain a large number of polygons and are very rich in geometric details, which presents problems for further use, such as visualization [11]. These methods are used in topographic mapping of large areas, heritage documentation, and geological structure modeling. Range-based methods can provide precise and complete details for small- and medium-sized objects with a high degree of automation [12]. Nevertheless, they are associated with high cost, weight, and a usual lack of good texture [23].

Several studies in the field of CH have employed range-based laser scanning to create 3D models. One example is Yastikli [30], who used Terrestrial Laser Scanning (TLS or Terrestrial LiDAR) to document the Muayede ceremonial hall of the Dolmabahce Palace in Istanbul. The survey was conducted using a laser scanner mounted with a digital camera, which collected 32 scans of the hall with 5mm accuracy. The calibrated digital camera was used to automatically assign an RGB value to each of the points in the point cloud. Fassi et al. [31] conducted four case studies, in which several large CH monuments and buildings were surveyed using laser scanning, including a church façade, a chapel and Roman thermal complex. Furthermore, Oreni et al. [32] outlined the use of laser scanning to model the Basilica of Collemaggio in Milan, Italy. A total of 182 scans were taken with an accuracy of 3mm, resulting in approximately 8 million points.

### Multi-sensor

Another common approach for 3D surveying of large and complex sites relies on the use of both image-based and range-based (LiDAR) together [23]. This is done because it exploits the advantages of each technique, it; compensates for their respective weaknesses; derives different geometric levels of detail (LOD) of the target site or object; and achieves more accurate and complete geometric surveying for the modeling, representation, interpretation, and digital conservation issues.

Several examples in the literature can be found in which researchers combine both surveying methods to create 3D models. Banfi et al. [33], for example, employed both TLS and aerial photogrammetry to create a 3D model of the San Nicoló church in Italy. Andrés et al. [34], in turn, conducted a case study on the Antioch Gate in Aleppo where

a virtual 3D model was generated to help the restoration process. The model was generated using photogrammetry and TLS, using robust methods to create parametric surfaces from a triangulated mesh. Moreover, El-Hakim et al. [35] used image-based techniques to model basic shapes and structural elements, while using range-based methods (laser scanning) to model fine details and sculpted surfaces for an abbey in Pomposa Italy.

### **Comparison**

All three methods mentioned above have been used in the context of CH, and all of which have their own strengths and weaknesses. Comparing the capabilities of each approach could provide some insight into which applications they serve best. Photogrammetry is capable of creating accurate 3D models of wide and complex models [31]. Moreover, it gives models a photorealistic look and makes a true copy of the real object [5]. One of the main advantages of using photogrammetric data processing in the development of CH models is that it allows a fully automatic approach without the use of targets. Moreover, image-based methods can give accurate results without the need for external intervention and are low cost, flexible, and fast [31]. LiDAR, on the other hand, provides a high-precision recording of the surface of the object [5]. Furthermore, the use of range-based methods, such as LiDAR, is better at providing full-resolution scans in real time, as photogrammetry can take a long time to process large numbers of photos [31]. As mentioned above, combining these two methods into a multi-sensor approach is commonly used within the CH field, providing the best results in terms of both appearance and geometric detail [23]. The main disadvantage of using this approach is that data acquired from different sensors need to be aligned and merged. If sensors use different geometric resolutions or viewpoints, it can affect the accuracy of the 3D model if it is not properly considered and handled [23].

### **3D Modelling**

The surveying techniques mentioned in Section 4.2 do not result in informative 3D models. Rather, they result in point clouds from the surveyed object/site that need to be processed to generate textured, surfaced 3D models. *3D Modelling* refers to the process of generating such a 3D model from point clouds, and there are two main aspects to consider in this process: morphological and typological. *Morphological* refers to the shape of the model (converting point clouds into objects with minimal deviation), while *typological* refers to the possibility of linking different types of information to the models, even segmenting them into smaller parts. There are three main 3D modelling techniques to model point cloud data in the CH domain: *Mesh modelling*, *Non-Uniform Reation B-Spline (NURBS) modelling*, and *Historic Building Information Modelling (HBIM) modelling*. Each of these have their own advantages and disadvantages, applications and require different levels of expertise [33], which is described below.

#### **Mesh modelling**

A polygon mesh is a collection of vertices, edges, and polygons that define the shape of a 3D object. Polygon meshes are often automatically generated from the point clouds

collected, either by a third-party software or in the data collection software itself. Such a mesh contains a number of vertices with edges connecting them together and polygonal faces filling the holes. Software, such as MeshLab<sup>1</sup>, Meshroom,<sup>2</sup> and Bentley ContextCapture<sup>3</sup>, use specific algorithms to automatically create a polygonal mesh from dense point clouds. The algorithms take the point clouds as input and output a polygonal mesh representation of the object. The process of turning a point cloud into a mesh can be simply explained as converting each point in the point cloud into a vertex and generating polygons to connect all of them together. This is the main disadvantage of using mesh modelling. If the point cloud is dense and large, the corresponding mesh model will have a large number of vertices and polygons. The size of the generated mesh will therefore be large, limiting its use in other software or requiring excessive processing power to render [33]. When a mesh has a large number of vertices and polygons, it is considered a *high poly* mesh. There are algorithms and techniques to reduce the number of polygons called *polygon decimation*. If a high poly mesh is decimated, the resulting mesh has fewer polygons and is considered a *low poly* mesh of the model. The advantage of decimating a high poly mesh is that the size of the model will decrease and, therefore, require less processing to render. The main disadvantage is that as the model decreases its polygon number, the level of detail in the model decreases.

There are many examples of mesh modelling being used in the context of CH, as it can easily be generated from point clouds by different software. One example is the study by Rahaman et al. [10]. Their work used a textured mesh model to visualize a frog sculpture and a building. Kersten et al. [36] also used a polygonal mesh to generate a model of the fortress Al Zubrah for the Qatar Islamic Archeology and Heritage Project with the goal of providing detailed 2D/3D documentation of the fortress. Additionally, Shih et al. [27] adopted the mesh modeling approach to display old cultural elements of different sizes and shapes.

### Free-form modeling using NURBS

Non-Uniform Rational Basis Spline, or NURBS, is a mathematical model commonly used in computer graphics to represent curves or surfaces. It is a form of curve modelling, where a single NURBS curve can represent a surface that would have required a large number of vertices in a mesh. A NURBS surface is the function of two parameters (control point and control mesh) that maps to the surface in the 3D space, determining its shape. Free-form modelling can be done using NURBS algorithms to reach higher levels of detail [33]. The main tools that offer free-form modelling with NURBS algorithm are: McNeel Rhinoceros<sup>4</sup> and Autodesk®AutoCAD.<sup>5</sup>

The main advantage of using NURBS is that it requires little data to model complex shapes, as you only need to store the control polygon points. It can also model any

<sup>1</sup><https://www.meshlab.net/> (As of June 2022).

<sup>2</sup><https://alicevision.org/#meshroom> (As of June 2022).

<sup>3</sup><https://www.bentley.com/en/products/brands/contextcapture> (As of June 2022).

<sup>4</sup><https://www.rhino3d.com/> (As of June 2022).

<sup>5</sup><https://www.autodesk.com/products/autocad/overview?term=1-YEAR&tab=subscription> (As of June 2022).

shape, such as a perfect circle. The main disadvantage is that they are hard to texture, as each NURBS surface has its own UV mapping, which is used in mesh modelling. U and V are the coordinates used in textures that correspond to X and Y coordinates in a 2D coordinate system. U is the direction that goes from side to side in a quadratic sheet, while V is the direction from top to bottom. Using UV mapping for texturing allows for more seamless textures, as all polygons can share the same texture. As each NURBS surface is individually textured, this may lead to misalignment of the textures of the different surfaces, resulting in an unrealistic appearance on the model if the texture is complex and detailed.

Several studies have explored the use of NURBS in CH, most of them for larger structures and buildings. F. Diara et al. [37] employed the NURBS modeling approach to model the Staffarda abbey in Italy using the Rhinoceros software to achieve a good LOD of the complex geometries and features of the building. Campbell [38] proposed a methodology to create cost-effective 3D models of old ships using NURBS modeling, as they are better at modelling the curvatures of the ship. Finally, Oreni et al. [32] modelled the Basilica di Santa Maria di Collemaggio in Italy using NURBS curves and surfaces due to the large final output models of mesh modeling.

### **Parametric HBIM modelling**

Historic Building Information Modelling (HBIM) is a form of Building Information Modelling (BIM) applied to existing buildings. It is a way to model historic structures based on survey data from the sites. HBIM is a reverse engineering process of BIM objects onto surfaces from scans to create a model of the historic structure [39]. HBIM models can not be directly modeled using point clouds and therefore need to be created using polygonal meshes or NURBS models. The main advantage of using HBIM is that it is possible to add parametric information about the building into the model. Parameters, such as type of material and construction method, can be embedded directly in the model [33]. One of the disadvantages of using HBIM is that most of the BIM tools were not designed to create models of existing buildings, so the process can be time consuming. Another is that BIM applications are complex tools and are not easily usable by non-experts in 3D digitization [26]. Moreover, HBIM models cannot be easily imported into all visualization platforms, often needing additional plugins and integration processes.

HBIM models have been used in the literature for archeological sites and historic buildings. Banfi et al. [33] employed the HBIM model for the archeological site of S. Nicoló in the village of Bajardo, Italy, creating granular models of all the major objects on the site. Fonnet et al. modelled the Ducal Palace in Guimarães, Portugal using HBIM models for the purposes of preventive maintenance in MR [40]. Additionally, Banfi et al. used HBIM modelling to represent the Arco della Pace (Arch of Peace) in Milan, Italy to explore the integration between HBIM and XR. Constantino et al. [41] modelled the church of San Nicola church in Italy using HBIM for the preservation and conservation of the building.

## 2.2.2 Immersive Technologies in Cultural Heritage

The potential of immersive technologies in the field of CH was identified early and has been investigated for more than 20 years [42]. There are several applications of XR technologies in the CH domain, whose purposes can be divided into five different categories [2]:

- *Education*: This category relates to the desire to disseminate information about CH sites and educate the public about the history and significance of the sites. The purpose of which is to let users learn about the historical aspects of tangible and intangible CH [2]. The use of AR in CH education has shown higher levels of motivation and interest from users [43].
- *Exhibition enhancement*: This category refers to attempts to improve the experience of visitors at CH sites or museums, typically guiding the user through a tour [2]. Furthermore, XR offers the opportunity to gamify CH (adding games or elements similar to a game), allowing a more entertaining presentation of content and improving the user experience [2].
- *Exploration*: This category aims to help users visualize and explore current and historical CH objects or landscapes to discover, interpret, and acquire new insights and knowledge [2].
- *Reconstruction*: This category concerns attempts to let users visualize and interact with reconstructed versions of CH objects and landscapes that have been damaged or lost [2].
- *Virtual museums*: This category refers to virtual reconstructions of a physical museum that simulate and present CH to the general public [2].

As the XR umbrella covers three technologies, the possible devices to access their experiences vary greatly. Moreover, many different types of devices are used for XR systems in the context of CH based on their specific purpose and object, and no device stands out as the industry standard. However, the different devices can be categorized into five main types [2]:

- *Head-Mounted-Display(HMD)* is a device that is worn on the head with a small optic in front of the eyes. HMDs are generally associated with VR, but can also be used for AR and MR. Common examples of such devices are as follows: Oculus Rift, HTC Vive, and Samsung Gear VR. There are cheap substitutes for these, such as Google Cardboard,<sup>6</sup> which can turn a smartphone into a HMD.
- *Spatial AR (SAR)* are devices that layer virtual information directly onto the physical environment, either by projection or holography, such as the Microsoft HoloLens. SARs are generally expensive and are not commonly used in CH, yet recent years have shown an increase in the use of this nascent technology [2]. Moreover, recent developments in smart glass technology and the investments of large companies such as Meta, Apple, and Google to create them [44], might make them more affordable and accessible.
- *Hand-Held Devices (HHD)* combine a digital camera, sensors (capturing position

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<sup>6</sup><https://arvr.google.com/cardboard/> (As of June 2022).

and orientation in world space), and a portable display to access XR experiences [2]. Some examples of HHD are tablets and smartphones.

- *Screens* comprise solely of a specific visualization display, such as a projector, a screen, or a set of screens. These types of display are often used in non-immersive and semi-immersive settings [2].
- *Cave Automatic Virtual Environment (CAVE)* is a room consisting of three to six walls where there is a set of projectors that display the experience in an immersive setting. CAVEs can be combined with input devices like gloves, joysticks, or sensors to allow user input into the experience.

### Virtual Reality (VR)

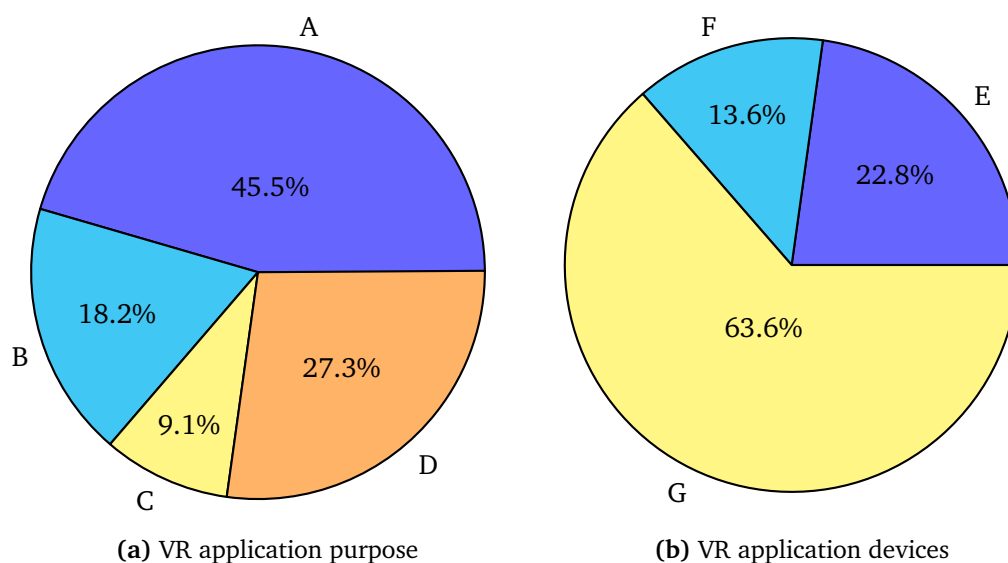
Virtual Reality has been a trending technology in the CH domain for more than 20 years [45], culminating in a wealth of research on its applications. One of the first programs to adopt VR in CH was ‘A journey through Ancient Miletus,’ which allows users to explore the city of Miletus in Greece as it was two thousand years ago [46]. The experience included reconstructed versions of many historic temples that the user was free to explore by walking or flying through the scene. The purpose of this application was to educate the user about ancient Greek culture.

### **Newer Applications and Devices**

Newer studies have used VR for several different purposes. Hakkila et al. [47] used the technology for reconstruction purposes to allow access to then inaccessible Salla World War 2 graveyard on the border between Finland and Russia. The main functionality of the experience was to teleport through the graveyard and place a lighted candle at any location in the scene. Banfi et al. [26] used VR to develop a Virtual Museum, allowing users to view models of the Arco della Pace monument in Milan, Italy, along with its statues, as well as video, audio and images taken from the site. Moreover, Donghui et al. [48] employed VR for reconstruction purposes by modelling parts of Rinjin City in China that had been lost.

The most popular application of VR in CH from 2002-2017 were virtual museums [2]. Due to its ability to completely immerse the user in a virtual world, a virtual replica of the museum containing interactive exhibitions is a common use of the technology. Less common applications are education, reconstruction, and exploration, respectively (the distribution can be seen in Figure 2.2a). Newer researches are more focused on reconstruction purposes, which might demonstrate a change in trends.

The newer research conducted by Hakkila et al. [47], Banfi et al. [26], and Donghui et al. [48] used HMD. The survey by Bekele et al. [2] discovered that the most popular devices used to experience VR applications between 2002-2017 in the CH domain were screens, followed by CAVE and HMD (the distribution can be seen in Figure 2.2b). This indicates a change in the VR device trends. Most recent initiatives use HMD, which might suggest that such devices have become more accessible and affordable.



**Figure 2.2:** The distribution of surveyed VR applications (between 2002-2017) by (a) purpose and (b) devices [2], where:

(a): A = Virtual Museum, B = Reconstruction, C = Exploration, D = Education

(b): E = CAVE, F = HMD, G = Screen/projector

### Benefits and Challenges

The adoption of VR in the field of CH has brought many benefits, including

- *Learning:* One of the benefits of using VR in CH was the increase in learning outcomes for visitors [49]. Learning from VR is easier than learning from books because it provides interactivity, various means of communicating factual information, and gives a sense of transportation to a different culture.
- *Accessibility:* VR adoption has been shown to increase CH accessibility [50]. One example refers to sites where fragility and safety concerns limit the access of visitors. In this case, VR can be adopted to allow full exploration without risking the actual site. This was shown to increase interest in cultural sites and the importance of conserving them [50].
- *Exploration:* Additionally, exploration was identified as a benefit of VR adoption in CH [51]. Virtual tours that explore historic and cultural sites can be enjoyed by anyone, which could benefit people with impaired movement. They might also provide insights into different epochs of the site, rendering its evolution over time and allowing exploration in earlier stages of its development.

As the use of VR in CH is still in its early stages, there are still many challenges that researchers face when implementing the technology. The main ones are:

- *Affordability:* There are several challenges related to the cost of implementing a VR solution. Implementation requires a lot of resources in several aspects: large open space, expensive equipment, and the complexity of installing and maintaining the solution [52].

- *Cybersickness*: A common challenge in using VR in any context is “cybersickness,” a set of symptoms, such as headaches, nausea, disorientation, and vision problems associated with being immersed in the technology for prolonged periods [53].
- *Interaction*: VR aims to achieve a fully immersive experience, which means that it needs to emulate the way users interact with physical objects. This is difficult to achieve with the use of sensors or hand controllers, which can be too complex and do not provide haptic feedback [52].

### **Augmented Reality (AR)**

One of the first adoptions of Augmented Reality in the field of CH was by Vlahakis et al. [54], in 2001, with the Archeoguide project [54]. They developed an AR application to guide users through the archaeological site of Olympia. Moreover, it allowed the user to view reconstructed versions of the temples and animated activities, such as avatars competing in the stadium. Since then, the use of AR has gained popularity in the CH field. In 2009, Choudary et al. [55] proposed a solution for MARCH (Mobile Augmented Reality Cultural Heritage) to enhance the discovery of CH by adding expert drawings of cave paintings on top of prehistoric cave engravings.

### **Newer Applications and Devices**

More recent studies have been conducted in the field, where AR has been used for several different purposes. Sauter et al. [56] used the technology for exploration purposes by overlaying historic images over the phone’s camera based on location. Ntagiantas et al. employed AR for educational activities related to teaching children about the pastoral life of Psiloritis in Greece through AR books. Kadri et al. [57] used AR for the purposes of a Virtual Museum encouraging tourists to visit and discover the CH of Fez in Morocco using the ARCore SDK.

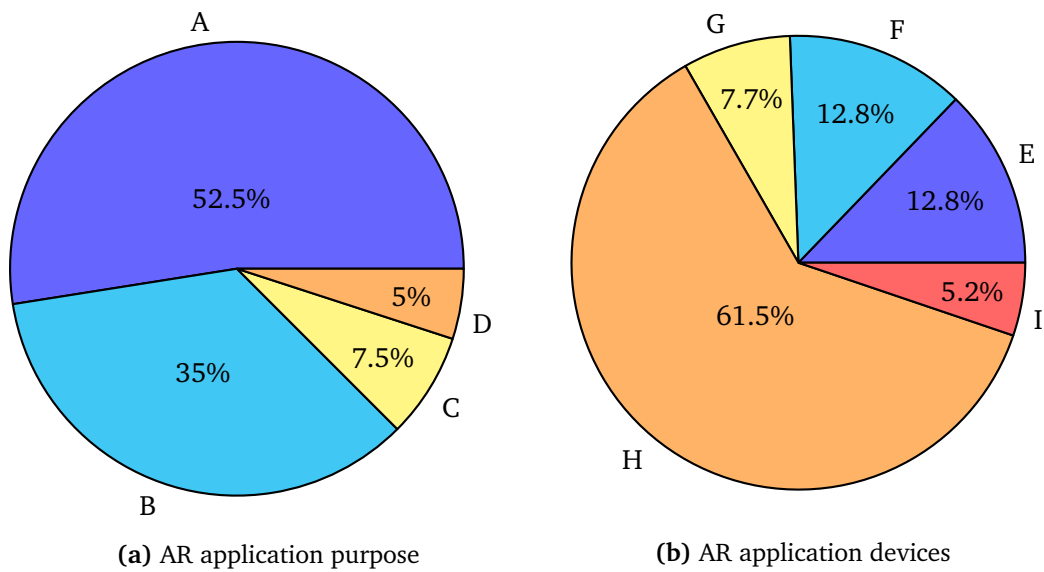
There are many different purposes for applying this technology in the context of CH, although it was primarily used between 2002 and 2017 to enhance the overall experience of the visitor to a CH site [12]. Other purposes include reconstruction, exploration, and education [2]. The distribution of application purposes can be seen in Figure 2.3a, which could indicate a change in trend, as the newer studies outlined no longer focus on exhibition enhancement.

Recent studies in the literature, such as Sauter et al. [56], Kadri et al. [57], and Ntagiantas et al. [58], used mobile phones as AR devices. This fits the older trend in the literature, where most AR applications between 2002 and 2017 in the CH domain use mobile phones as their devices [2]. This could be due to the increasing processing power of existing smartphones and their increased accessibility and affordability. The distribution of devices used in the CH domain can be seen in Figure 2.3b.

### **Benefits and Challenges**

Some studies have examined the value AR brings to the CH domain [59], concluding on several aspects where different stakeholders benefit from the technology:





**Figure 2.3:** The distribution of surveyed AR applications between (2002-2017) by (a) purpose and (b) devices [2], where:  
 (a): A = Exhibition Enhancement, B = Reconstruction, C = Exploration, D = Education  
 (b): E = HMD, F = Combo, G = Desktop, H = Mobile Device, I = Other

- *Reconstruction of missing parts:* Some CH artifacts, monuments, and buildings are old and therefore have degenerated in some way, missing some parts of their original construction. AR allows these missing parts to be digitally reconstructed and added back to the object, without posing risks to them [60].
- *Economic:* There were several aspects of AR use in CH that showed economic benefits, such as increasing sales, providing incentives to return, and attracting new target groups [59].
- *Experiential:* The ability of AR to add interactivity makes the experience more exciting and interesting, resulting in enriched memories and improved emotional attachment [59]. The use of AR in museums for reconstruction can significantly enhance the visit for experts and non-experts by showing how certain exhibits may have looked in the past [60].
- *Social:* Due to the gamification ability of AR, users have reported social benefits such as improved social interaction, improved sharing ability (experience and scores), and social fulfillment [59].
- *Epistemic:* This aspect relates to users' curiosity about trying new products and their willingness to experience something new [61]. AR in CH has been reported to have several epistemic benefits, including curiosity to try new technology, a new concept of engagement, and increased attention [59].
- *Educational:* As was the case with VR, AR showed benefits for educational purposes by allowing a personalized learning experience in which the user could learn at their own pace, provided an easier medium to memorize information, and created a more enjoyable and interactive learning experience [59].

As with all new technologies, there are also many challenges related to the implementation of AR in CH. Some of the main ones include:

- *Tracking limitations*: Tracking is a vital component in AR, as it requires knowledge of the physical world to function correctly. Different types of sensors track the necessary information about the surroundings (e.g., optical, location, orientation), but these can sometimes be inaccurate. Difficult conditions, such as poor lighting and weather conditions, can cause the trackers to be even more inaccurate and result in a less enjoyable and immersive experience [62]. CH is often displayed in museums with low-lighting or in outdoor setting, where conditions can vary greatly.
- *No established standards*: Developing AR solutions can be difficult, as there are so many different toolkits, software, and tools available, resulting in a choice overload [62]. Each operating system has its own AR toolkit (ARKit<sup>7</sup> for iOS and ARCore<sup>8</sup> for Android), and there are a number of free open-source options (e.g., PanicAR,<sup>9</sup> DroidAR,<sup>10</sup> and ARToolkit<sup>11</sup>), all of which offer different tracking options.
- *Lack of real-life applications*: Most AR systems developed in the literature exist only as research projects, often a way to test new technologies, sensors, tools, or hardware. Most do not provide a system that CH institutions can use [62]. However, the introduction of AR on social media and the increase in the affordability and accessibility of smartphones have led several museums to adopt AR to showcase CH exhibits in AR [63].

### Mixed Reality (MR)

MR is not as widely used in the CH domain as AR and VR, which may be due to the fact that the technological aspects of MR are still in their infancy [2]. There are also some different definitions of Mixed Reality, some defining it as an umbrella term for VR and AR [64, 65]. However, one of the first MR projects to be introduced was the CREATE project which was introduced in 2003 on a global scale to promote the development of MR projects in CH [66]. That project proposed a framework for creating highly interactive MR experiences from real data. It was tested in a case study in which the objective was to understand and learn about ancient Greek architecture and was used by archaeology students to validate several reconstruction hypotheses.

### **Newer Applications and devices**

Since these initial solutions, the use of MR in CH has grown in popularity, with more studies exploring its possibilities. Teruggi et al. [67] employed MR for the purposes of education, by developing an MR application that allowed users to interact with segmen-

<sup>7</sup><https://developer.apple.com/augmented-reality/arkit/> (As of June 2022).

<sup>8</sup><https://arvr.google.com/arcore/> (As of June 2022).

<sup>9</sup><https://github.com/VuframeLab/PanicAR> (As of June 2022).

<sup>10</sup><https://bitstars.github.io/droidar/> (As of June 2022).

<sup>11</sup><https://github.com/artoolkit/ARToolKit5> (As of June 2022).

ted 3D models of the Milan Cathedral in Italy. The users could select a component of the Cathedral, such as a column, and be shown associated textual information about that component. Bekele [68] explored the use of MR for exhibition enhancement purposes by providing a walkable map to guide users through historical sites. The interaction method ‘Walkable MR Map’ was proposed, which allows the user to interact with virtual objects via maps that are virtually projected onto the floor. Additionally, Rahaman et al. [10] used MR for exploration purposes to showcase and interact with CH objects that had been 3D reconstructed developed using Unity.

The most common use of MR in the CH domain in 2002-2017 was for reconstruction purposes, followed by education, exploration, and virtual museums, respectively [2] (distribution can be seen in Figure 2.4a). The newer studies outlined in this section all have different purposes, none of which are the same as the most common ones found by Bekele et al. [2], indicating a change in trends.

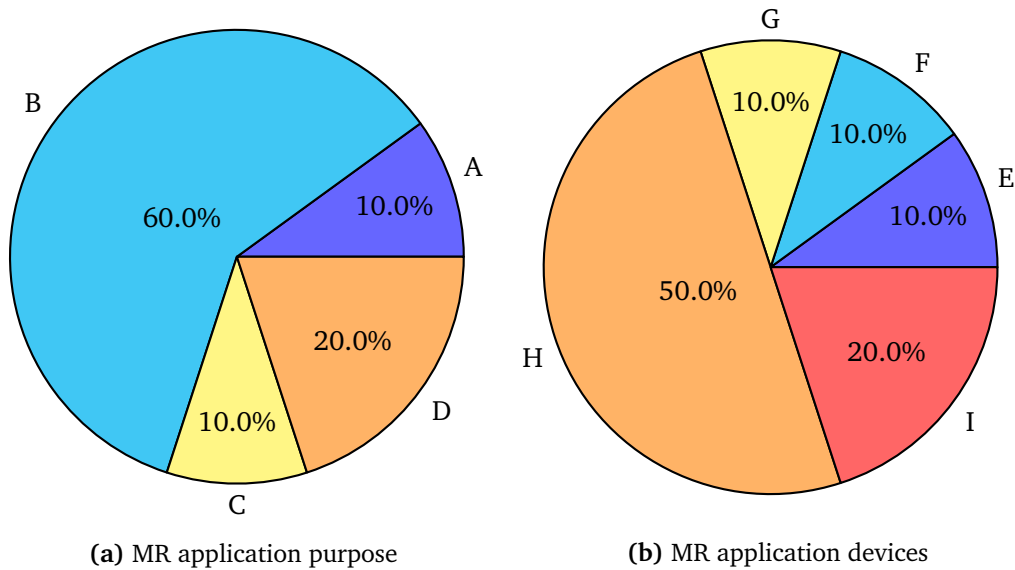
MR also supports a wide variety of devices, but some are used more frequently for CH purposes. Teruggi et al. [67] used the Microsoft HoloLens 2 as their display device, allowing interaction and alteration of the 3D models displayed using hand gestures. In their study of the ‘Walkable MR Map’, Bekele [68] used the Microsoft HoloLens to superimpose the maps onto the floor and allow for basic interaction based on gesture, gaze, and voice interaction. Rahaman et al. [10] also used Microsoft HoloLens to display the reconstructed 3D models. In their review of MR applications from 2002-2017, Bekele et al. [2] found that the most common device to display MR in CH is mobile phones, but some use specialized HMD equipment, such as Microsoft HoloLens, which can display combined real and virtual content. The distribution of devices used for MR applications in CH can be seen in Figure 2.4b, indicating a change in trend as newer papers outlined in this section all use Microsoft HoloLens. This might suggest that such devices have become more accessible for use in the CH domain.

### Benefits and Challenges

The use of MR allows more interaction in the experience, as it is one of its defining characteristics. Interaction between user and virtual object, but also between the object and the physical environment, results in a number of benefits for the user, such as:

- *Increased appeal for youth*: Younger people, generally referred to as Generation Z, become more easily bored and require fast and interactive experiences that address their curiosity [1]. The introduction of MR in CH can improve its appeal to younger people, attracting more of them to visit.
- *Interaction with protected objects*: One of the most frustrating aspects of visiting museums is that everything is hidden behind a glass or is not allowed to touch. This missing interaction leads to boredom, especially for young people [1]. MR can allow visitors to CH sites to interact with virtually reconstructed versions of the objects, without the risk of damaging fragile artifacts.

As MR is the newest addition to the XR family, it also comes with a special set of challenges. Many of the same challenges faced for the others also apply to this technology, but the main ones for MR use are:



**Figure 2.4:** The distribution of surveyed MR applications (between 2002-2017) by (a) purpose and (b) devices [2], where:  
 (a): A = Virtual Museum, B = Reconstruction, C = Exploration, D = Education  
 (b): E = HMD, F = Combo, G = Screen/projector, H = Mobile Device, I = Custom

- *Merging virtual and physical worlds:* The ability of MR to offer a high level of interactivity between the virtual and physical worlds requires many sensors to accurately map the environment. This poses a calibration challenge in seamlessly merging the virtual and physical worlds, as any inconsistencies of positioning between the virtual object and the physical world will degrade the immersion of the experience [69].
- *Equipment:* Although MR can be accessed through smartphones, more immersive applications of the technology require expensive and specialized equipment, which is still in the prototype phase [70]. These are not widely accessible to the public, but recent developments in the smart glass industry could change this limitation.

### 2.2.3 Existing Pipelines

There are several pipelines that have been proposed covering the process from 3D reconstruction to immersive experiences in XR. In total, ten pipelines were found; they comprise parts of or entire workflows to facilitate the construction of such experiences. Out of those ten, seven were selected as part of the literature review, as they proposed complete pipelines from 3D reconstruction to XR experience in the context of CH.

One of the first pipelines introduced in the literature was by Wojciechowski et al. [71]. Their system allows museums to build and manage VR and AR exhibitions based on 3D artifact models, which content designers could use to efficiently create virtual exhibitions. The developed system architecture, named ARCO, consisted of three main

components: content production (all tools and techniques used to create 3D models of artifacts), content management (model storage and access), and content visualization (VR and AR interfaces).

H. Rahaman et al. [10] presented a methodology on 3D digitization to MR visualization of CH assets based on open access software and services. Through two case studies, they created 3D digital assets using photogrammetry and presented them in an interactive MR environment using Microsoft HoloLens<sup>12</sup> to support visualization and learning of CH.

Bruno et al. [42] proposed a methodology for the realization of an integrated virtual exhibition system in VR. It recreated a rich archaeological collection with a relatively low budget, defining guidelines for the development of such exhibitions that could be used by local authorities and small museums.

García-León et al. [9] defined a pipeline ranging from 3D documentation and reconstruction of a complex work of art to an interactive experience in a game engine. The paper outlines a case study related to the Santo Domingo church in Cartagena, Spain, where an altarpiece was reconstructed as a parametric 3D model and added to an interactive VR experience developed in Unreal Engine<sup>13</sup>.

Banfi [33] proposed a pipeline on how to create granular HBIM models from point clouds and import them into a VR project. They surveyed the ruin of the San Nicolò church in Bajardo, Italy, using TLS and photogrammetry to create a HBIM model of the site using manual generation of wireframe models. This resulted in a Scan-to-HBIM-to-VR method that allows the decomposition of HBIM models into more detailed granular objects and exploring them in a virtual museum using VR.

Banfi et al. [26] proposed a Scan-to-HBIM pipeline that explored how novel XR environments can convey the history of cultural heritage monuments, using new formats, new game engine platforms, and visual scripting to provide an architectural study of the Arco della Pace in Milan, Italy. The authors developed several XR experiences, including a VR virtual museum, to show HBIM models of the monument and its statues, as well as video, audio and images taken from the site. The model was generated using laser scanning and aerial photogrammetry using a UAV. The objective of the research was to provide a larger audience with the enjoyment of the architectural, artistic, and cultural heritage contained in such historic monuments.

Gaugne et al. [72] proposed a general pipeline starting from the digitization of CH material and with the aim of creating immersive experiences to be used by CH experts. The authors present several case studies developed in collaboration with archaeologists, historians, and computer scientists that illustrate different interactions in functional and operational 3D environments.

The pipelines outlined focus mainly on one specific implementation of a pipeline rather than providing generic steps. They are developed for a specific surveying technology, equipment, tool, or platform, which limits their usefulness to applications that desire a similar outcome. Moreover, the majority applies tools and techniques that require expertise within their use, making it difficult for non-experts to follow their guid-

<sup>12</sup><https://www.microsoft.com/en-us/hololens> (As of June 2022).

<sup>13</sup><https://www.unrealengine.com/en-US> (As of June 2022).

ance. However, some pipelines reject this approach to provide general pipelines [72] and workflows suitable for non-experts [10].

## Chapter 3

# Proposed Pipeline

This chapter outlines the proposed generic pipeline for creating Immersive Virtual Heritage Experiences, hereinafter referred to as the IVHE pipeline. This chapter describes each step of the process from surveying a real-world CH object or site to displaying it as an immersive experience in XR.

### 3.1 Immersive Virtual Heritage Experience pipeline

The entire process of creating VH experiences using immersive technologies can be described as a pipeline, as there are a number of steps that must be completed chronologically for this experience to manifest. There are several pipelines that have been proposed that provide a complete [9, 10, 26, 33] or partial [4, 5] workflow of how to create immersive VH experiences. However, they all offer very narrow implementations, outlining steps to create experiences using specific tools, modelling techniques, or platforms. Moreover, most of them require high-level knowledge of specific complex techniques and tools, making them difficult to follow for non-experts. The IVHE pipeline is expected to be as generic and simple as possible, providing a workflow to create immersive experiences of CH that can be followed regardless of expertise or technical decisions, such as equipment, tools, techniques, or platforms. This limits the ability to provide detailed instructions on how to perform each individual task (since they will depend on the project specifications and technical decisions) and only provides an overview of the required steps. However, there is a wealth of information online on how to perform each of the steps described for any and all technical decisions a specific project needs to make.

The entire IVHE pipeline (shown in Figure 3.1) is divided into three main stages: (1) Surveying, (2) Modelling, and (3) Immersive Experience. The *Surveying* stage contains the steps to collect 3D data on the CH object or site, while the *Modelling* stage outlines the steps to finalize the 3D model to use. Finally, the *Immersive Experience* stage details steps needed in the process of creating the XR experience and deploying it on a device. In total, the pipeline contains 12 steps that range from surveying the CH object to creating an immersive experience with possible shortcuts that can reduce this number.

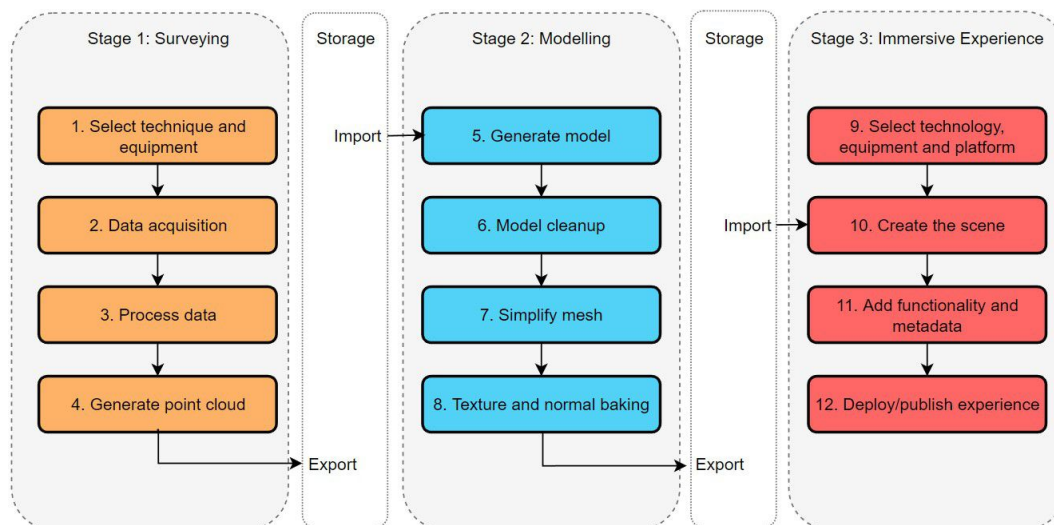


Figure 3.1: Complete IVHE pipeline.

## 3.2 Surveying

Acquiring data on the selected CH object/site is the first stage of the IVHE pipeline, which is carried out by 3D surveying of the target. This stage of the pipeline is adapted from the study conducted by Rahaman et al. [10], who followed six steps in their 3D reconstruction process: (1) data acquisition, (2) data alignment, (3) point cloud generation, (4) dense cloud generation, (5) mesh generation, and (6) texture generation. Steps 1-4 are relevant in the context of surveying, while steps 5-6 are related to modelling and were therefore omitted from this stage. As the IVHE pipeline does not target any specific tool or technique, an additional step was added in the beginning to address these aspects. In addition, the two steps of point cloud generation (3-4) were combined into a single step, resulting in a process consisting of four main steps: (1) selecting the surveying technique and equipment, (2) data acquisition, (3) data processing, and (4) point cloud generation (see Figure 3.2).

1. *Select technique and equipment*: In the context of CH, there is a wide range of different artifacts, sites, buildings, and monuments to document, each of which has different sizes, conditions, and levels of detail. The first step in the pipeline is to select the technique that will be used to document the CH asset. Based on the individual target, budget, and desired model, a decision must be made on whether to use image-based, range-based, or multisensor techniques to survey the object or site (a comparison of which can be found in Section 2.2.1). Additionally, the appropriate equipment must be selected for the survey target based on the chosen technique. Several of the same aspects must be considered when selecting the equipment, but the main consideration will be the size of the target and whether aerial scanning is needed.
2. *Data acquisition*: The second step is the acquisition of data on the target using the



selected equipment. Images or laser scans are collected from the site or object, from many different angles and locations, to document the target in its entirety. There are several logistical aspects to consider when planning the data acquisition of a CH object or site, as they are often fragile and only accessible for a certain amount of time. The most important aspects to consider when planning are: the time available for collecting data, the degree of interaction allowed with the object / site, the presence of obstacles, and the need to reposition the objects [9]. Moreover, on the basis of its dimensions, it can be beneficial to define data acquisition protocols, as these will help produce the best results [73].

3. *Process data*: The third step in the 3D surveying pipeline is to process the data collected from the site or object. For image-based surveying, this means reviewing the data set and selecting the best images. Generally, convergent imagery taken from a higher angle with the least amount of overlapping images will result in acceptable point clouds [73]. For range-based surveying, each 3D scan must be processed by removing erroneous points and outliers [11]. Removing these redundant points will speed up the generation of the completed point-cloud.
4. *Generate point cloud*: The final step in the 3D surveying pipeline is to generate the point cloud from the acquired data, the process of which will depend on the surveying technique employed. For image-based surveying, images can be imported into photogrammetry software, such as Regard3D<sup>1</sup> (this process is detailed in [10]), to generate a dense point cloud. For range-based surveying, the different scans must be aligned in a single point cloud by *registration*, which can be done automatically using software, such as Trimble RealWorks<sup>2</sup> and Leica Cyclone.<sup>3</sup> After the point cloud has been generated, it needs some post-processing before it is finished, as errors and outliers need to be removed. The point cloud then needs to be exported to a widely accepted format, such as .PLY, so that it can be used in the next step in the pipeline.

There are shortcuts in this process, and some applications remove the need to complete each step in the above pipeline, reducing the amount of time it takes. There are several free and commercial mobile applications (such as Polycam<sup>4</sup>) that can be used to automatically generate a textured mesh from images taken of the target through the application. There are also desktop applications that can provide similar shortcuts, such as Meshroom, which integrates the entire photogrammetric pipeline. The user only needs to input images, and Meshroom can generate a textured mesh from the data. These tools can be beneficial for non-experts or projects where the time budget is very limited, but for projects where control over the entire process is required, following each step can be favorable. Furthermore, the use of ‘shortcut’ software restricts the possibility of trying different algorithms and tools to compare models and obtain the best results.

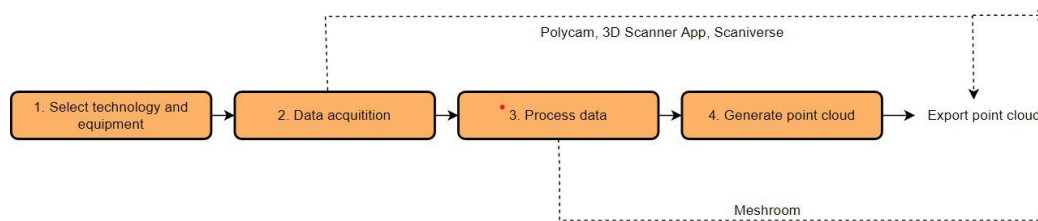
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<sup>1</sup><https://www.regard3d.org/> (As of June 2022).

<sup>2</sup><https://geospatial.trimble.com/products-and-solutions/trimble-realworks> (As of June 2022).

<sup>3</sup><https://leica-geosystems.com/en-us/products/laser-scanners/software/leica-cyclone> (As of June 2022.)

<sup>4</sup><https://poly.cam/> (As of June 2022).



**Figure 3.2:** IVHE Stage 1: Survey workflow.

### 3.3 Modelling

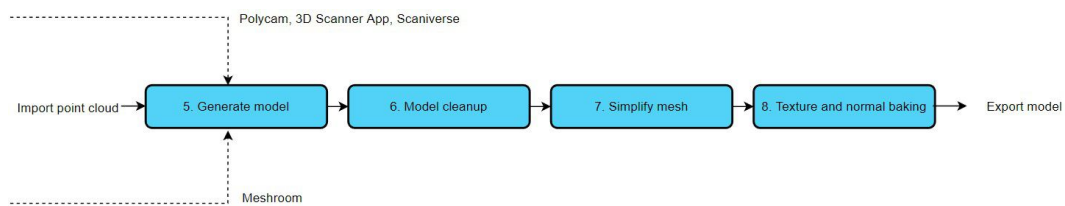
The second stage of the IVHE pipeline is to finalize the model to be used in the immersive experience, the main steps of which can be seen in Figure 3.3. As described in Section 2.2.1, there are three main ways to model the point clouds generated from the surveying stage: mesh modelling, NURBS modelling, and HBIM modelling. Nevertheless, mesh modelling techniques will be adopted for this stage of the pipeline, as the models can be automatically generated from point clouds, making them ideal for non-experts. The purpose of this pipeline is to be as generic and simple as possible, so using specialized modelling techniques like NURBS and HBIM would alienate non-experts.

There are several studies in the literature that provide a pipeline for creating NURBS and HBIM models [26, 33, 37]. Those models can then be reintroduced for the next step in the IVHE pipeline, which refers to the creation of immersive experiences. Moreover, mesh models can be converted into both NURBS and HBIM models with additional processing.

This stage in the pipeline is a modification of the 3D model optimization stage proposed by García et al. [9], who employed techniques from the game development industry to generate and simplify their models. Their steps of segmentation and parameterization have been omitted, focusing only on the steps to prepare the model for import into an immersive experience. This stage consists of four main steps: (1) mesh generation, (2) model cleanup, (3) mesh simplification, and (4) baking (see Figure 3.3).

5. *Generate model*: The first step in the modelling stage is to generate the model. This is done by importing the point cloud into software for 3D mesh processing, such as MeshLab.<sup>5</sup> Such programs can provide several different algorithms for reconstructing the surface from a point cloud. The user can select the Ball Pivoting Algorithm (BPA), Screened Poisson algorithm, or Marching Cube algorithm, all of which create a textured polygonal mesh from the point cloud.
6. *Model cleanup*: The next step is to clean up the model that has been generated in the above step. A generated model from scan data is often geometrically ‘wrong,’ as most available scanning techniques cause severe scanning artifacts, such as noise, outliers, holes, or ghost geometry [74]. This requires some post-processing to clean the model before it can be utilized further. Many 3D modelling software,

<sup>5</sup><https://www.meshlab.net/> (As of June 2022).



**Figure 3.3:** IVHE Stage 2: Modelling workflow.

such as MeshLab and Blender<sup>6</sup>, offer tools to automatically remediate many of the artifacts. Nevertheless, some manual cleaning is necessary to remove unwanted parts of the model that are not needed in the final model.

7. *Simplify mesh*: 3D models generated from point cloud data are often very heavy models that contain a large number of polygons [32]. Such a model is generally denoted ‘high-poly’ and will require more processing power to render, which compromises the performance of the intended visualization platform. The process of mesh simplification, or decimation, turns the high-poly mesh into a low-poly mesh using algorithms that reduce the number of polygons while keeping the shape as close to the original as possible [10]. This can be done in several different ways, with most 3D modelling software providing tools to simplify the mesh in-app. The user can choose the reduction percentage, or desired number of polygons/faces, and the application will output a low-poly model.
8. *Texture and normal baking*: As the model is decimated, it loses a lot of its detail because the smaller number of vertices is not able to represent subtle surface changes. Moreover, the texture of the model becomes full of artifacts, as the topology of the mesh has changed along with the UV mapping of the object. To address this issue, the texture and normal baking process can be applied to the model to reintroduce the details of the high-poly model in the low-poly mesh [75]. This process is used in CGI to improve the visual appearance of low-poly models using consistent procedures [9]. The baking process can be done in most 3D modelling software and requires a UV unwrapping of the low-poly model, before it can be baked with the high-poly texture and/or normals.

The model has now been converted from a point cloud to a clean low-poly model that contains the texture and normal information of the high-poly model. This process has produced a light model with an appropriate number of polygons that can be imported into any visualization platform. If the CH object/site has many different objects or intricate features, this process can be repeated for each one. Before they can be imported, they need to be exported into supported file formats, like \*.FBX or \*.OBJ, that the platforms will accept.

<sup>6</sup><https://www.blender.org/> (As of June 2022).

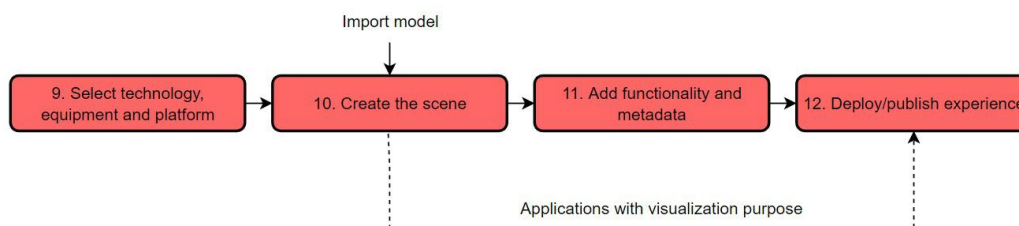
### 3.4 Immersive Experience

The final stage in the IVHE pipeline concerns the creation of the immersive experience that will be used to portray the CH object. The specific implementation of this stage will depend heavily on the desired technology, device, and visualization platform. There are still no common standards on which platforms to use in the CH domain, and studies select the platform that best suits their purpose. However, each immersive project has a generic process that needs to be carried out regardless of the selections mentioned above. This process can be divided into five main steps: (1) selection of technology, equipment, and platform, (2) scene creation, (3) functionality and metadata implementation, and (4) publishing experience (see Figure 3.4).

9. *Select technology, equipment and platform*: The first step in this process is to select the immersive technology desired (VR, AR, or MR ) to be adopted for the experience. Subsequently, the type of device to show the experience must be selected. Based on these choices, an immersive experience platform can be selected to develop the experience. Currently, there are several software frameworks that support AR/ VR that are especially suitable for CH, which have been evaluated in a study by Bekele et al. [2]. The study examines different platforms, exploring their strengths and weaknesses in a variety of settings so that the appropriate framework can be selected for a specific use case. Some common visualization platforms are: Unity 3D<sup>7</sup>, Unreal Engine, and Spark AR Studio. Additional toolkits may be required for a specific device or technology, such as ARKit, which allows the creation of mobile AR applications for iOS.
10. *Create the scene*: The second step is to create the scene that the user will enter through the experience. This includes importing the VH model created in the two previous stages of the pipeline, along with all other virtual models that the virtual environment should include. Then, the models need to be oriented and placed in their desired position in relation to the other models and the user.
11. *Add functionality and metadata*: After creating the scene, the functionality of the experience can be added to the platform. Based on the desired interaction and technology, scripts and modules need to be added to the scene to handle user input, such as hand and plane tracking. This step requires creativity from the experience developers to identify features that serve the intended purpose of the experience. Moreover, developers need a certain level of knowledge about coding to be able to efficiently script the functionality. If the experience's only purpose is to visualize the VH model, then there is no need for this step, and the experience can be deployed on the desired device only containing the scene. Metadata on VH models that provide additional knowledge and context about the object can be added in this phase, adding a new layer to the experience.
12. *Deploy/publish experience*: The final step in the pipeline is to deploy the experience so that the user can access it. This process will be different depending on the technology, platform, and device. The experience can be published on a VR mar-

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<sup>7</sup><https://unity.com/> (As of June 2022).



**Figure 3.4:** IVHE Stage 3: Immersive Experience workflow.

ketplace, posted on social media, or deployed on a specific piece of equipment, such as the Microsoft HoloLens.

### 3.5 Model Storage

To transfer the model between the different stages of the pipeline, it should be stored in a location that is easily accessible. Despite large initiatives to create digital heritage archives, VH 3D models are still not accessible to the general public [76]. However, there are several free and commercial repositories for storing 3D models, such as Sketchfab<sup>8</sup> and Turbosquid.<sup>9</sup> Cloud storage services, such as iCloud,<sup>10</sup> Google Drive,<sup>11</sup> and Dropbox,<sup>12</sup> can also be used to store the exported model, though this will make the model unavailable to the general public. None of the storage solutions mentioned above facilitates the management of related metadata, which needs to be stored and accessed separately from the 3D model. Another possible storage solution is to develop a dedicated digital archive with an accompanying API to post and fetch the models. This will allow for structured and dependable storage of the different models, so that they can be accessed and stored at all stages of its development (point cloud, raw model, cleaned, decimated, and textured). It will also allow for the storage of metadata, directly linking it to the target model, for easy retrieval of all data connected to a single CH object. Moreover, a digital archive of the models can foster collaboration on the development of the 3D models, as the same model can be accessed and edited by several developers. There are some examples in the literature of database architectures proposed to archive 3D models of CH objects [77, 78]. However, this is still an active research field, with many challenges still to be solved [79].

<sup>8</sup><https://sketchfab.com/> (As of June 2022).

<sup>9</sup><https://www.turbosquid.com/> (As of June 2022).

<sup>10</sup><https://www.apple.com/icloud/> (As of June 2022).

<sup>11</sup><https://www.google.com/drive/> (As of June 2022).

<sup>12</sup><https://www.dropbox.com/> (As of June 2022).

## Chapter 4

# Case Study

This chapter describes a case study conducted to validate the proposed pipeline. It outlines the execution of each stage in the IVHE pipeline for CH buildings at the Sunnmøre museum in Ålesund, Norway. The case study concerns the development of a mobile AR experience that allows the user to explore the exterior and interior of a CH building 3D reconstructed using multi-sensor surveying methods and mesh modelling. It follows the same structure as the pipeline, where Section 4.2 will describe the process of documenting and generating the point cloud, Section 4.3 refers to the generation of the model and how it was finalized, while Section 4.4, in turn, explains the process of creating and publishing the AR experience developed in Spark AR Studio.

### 4.1 The Cultural Heritage Buildings

The two buildings are located at the Sunnmøre Museum in Ålesund, where they were relocated from other parts of the Møre og Romsdal region for preservation and exhibition purposes. One of the buildings is a small wooden structure called a “drying room” (seen in Figure 4.1a) and was originally used to dry grain and malt for flour and beer, but could also be used to smoke meat, fish, and pork. It was originally located in Storvik, Ørskog but was disassembled and reassembled on the premises of the museum. The other building was a larger “cowshed” (seen in Figure 4.1b originally located at Fiskå, Vanylven and this type of building was common on Sunnmøre farms until the 1850s. It was used to house domesticated animals and consisted of ten cow stalls, a sheep pen, and a bunk for the maid. The building also had a small pig shed attached to it.

These particular buildings were selected for several reasons: location, surrounding landscape, and size. The buildings were located at the museum, which is an outdoor area in close proximity to the NTNU campus, Ålesund. This allowed easy access to visit, explore, and scan the building without significant time and traveling investments. In addition, the surrounding landscapes of the buildings made them easy to scan, having clear and open spaces around them that allowed for free movement. They are both also relatively low buildings, which eliminated the need for aerial scanning. Moreover, these buildings are not located at their historic locations which allows them to be reintroduced there using the developed AR experience.



(a) The “drying room.”

(b) The “cowshed.”

**Figure 4.1:** The Cultural Heritage buildings used for the case study.

## 4.2 3D Surveying

With the permission of Sunnmøre museum, the scanning of the buildings began as soon as the equipment was acquired. Both buildings are located outdoors, and surveying their exterior was possible at any time. However, scanning the interior required an employee at the museum to unlock the door, as they are usually closed for the general public, which required more careful planning and coordination with the museum staff.

### 4.2.1 Selecting Technique, Equipment and Tools

The first step in the pipeline is to select the technique and equipment necessary to survey the buildings. For the surveying step, a multisensor approach was selected as it provides the best results in terms of both appearance and geometric detail [23]. Moreover, it seems to be the state-of-the-art approach in the field of CH.

The iPhone 13 Pro Max was chosen as the main piece of equipment in data acquisition. This was due to the fact that it was equipped with a LiDAR sensor (with a range of 5 m and an accuracy of 5 mm) and a digital camera, making it ideal for the multi-sensor approach. Moreover, there exists a number of free and license-based mobile applications that allow the entire surveying process to take place in a single tool, from data acquisition to mesh generation, eliminating the need for many of the manual data processing steps. These applications, combined with the iPhone, make such an approach ideal for non-experts, as both the iPhone and its applications are highly intuitive and many people are already familiar with the iPhone. Three applications were selected to be used in the 3D scanning process: *Polycam*, *3D Scanner App*, and *Scaniverse*, all of which are free to download, some offering additional features for a monthly fee. To scan the entire building, a Dispho Bluetooth selfie stick was used, allowing access to higher points on the building that were difficult to reach.

## 4.2.2 Data Acquisition

Data acquisition was carried out in several different ways and a total of four surveys were carried out under varying conditions using all three applications. The first scan was conducted on February 22, 2022, to test the applications and equipment. There was snow in Ålesund at that time, which proved to be difficult conditions to scan, as it made the surrounding landscape harder to traverse and the resulting scans had snow in them. Therefore, the surveying had to be halted until conditions improved, which they did at the end of March, when all remaining scans were conducted. The interior of the “cowshed” proved to be difficult to scan, as its layout was complex and poorly lit. Several attempts were made to remedy the situation by doing several scans and merging the results in post-processing, but they proved too time-consuming and generated poor results. The “cowshed” interior was therefore omitted from the rest of the pipeline.

To ensure accurate and consistent data for all scans, it was necessary to develop a protocol for conducting them. This makes it possible to compare the effectiveness of the three applications by limiting the factor of human error in the scanning. The developed procedure was implemented as follows:

- Start and stop at the same location, preferably a corner of the building.
- Move slowly around the building in a clockwise direction.
- Keep the same distance to the building while moving (where possible).
- Point the phone from bottom to top, then from top to bottom at the next location.
- Spend extra time on detailed parts of the building, such as corners.

This procedure was refined over time and was the result of a trial-and-error process. The trajectory of one of these scans can be seen in Figure 4.2, in which the green points in the image indicate the position where an image was taken. Scanning in each application is very intuitive and has a similar UX. The initial view shows the camera and offers options for different scan modes and the desired range of the LiDAR scan. A record button is pushed to initiate a scan, and the parts of the object that have already been scanned will be shown on the screen. This allows the user to easily view the recorded parts and can adjust the angle or position of the camera to capture areas not previously scanned. When the entire building has been scanned, a stop button is pushed, and the application will generate a view of the recorded point cloud.

## 4.2.3 Point Clouds

The use of the above mentioned applications eliminated the need to process and generate scan data (steps 3-4 in the pipeline), as it was automatically done in the app. The generated point clouds for each building (interior and exterior) were exported to a colored.PLY format and imported into MeshLab for analysis. There were major differences in the size and number of points for each application, with Polycam providing the largest point cloud, both in terms of size and number of points, for the “drying room” interior, yet generating the smallest interior point cloud in terms of file size for the same building. A comparison of the different point clouds generated for each building can be seen in Table 4.1.



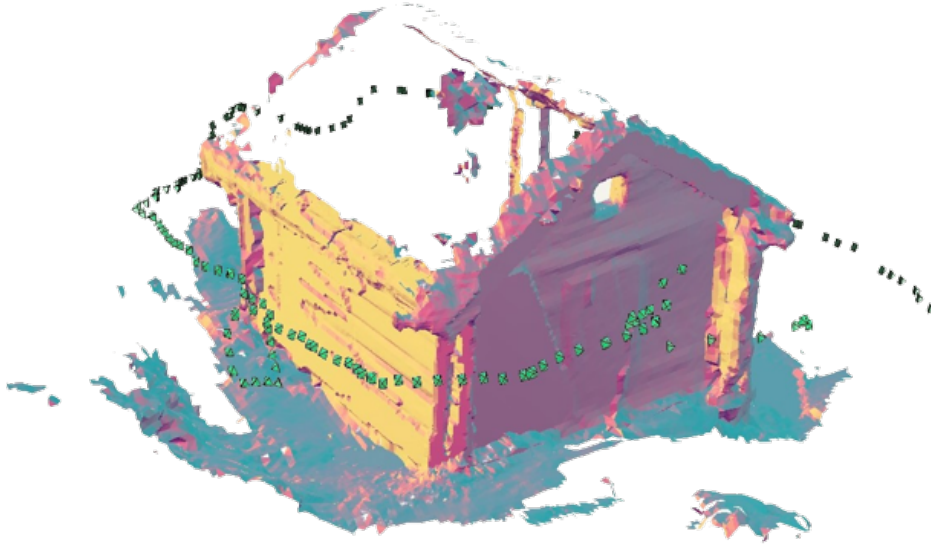


Figure 4.2: Scanning trajectory of the “drying room” building.

Table 4.1: Comparison of the point clouds generated by application, where *Poly* = Polycam, *3D* = 3D Scanner App, and *Scan* = Scaniverse (number of points shown in millions (MM)).

App	Poly	3D	Scan	Poly	3D	Scan
<b>Building</b>	“Drying room” exterior			“Drying room” interior		
<b>Points (MM)</b>	5.86	0.94	1.69	0.26	0.22	0.15
<b>Size (MB)</b>	154.9	73.1	19.8	6.9	16.8	21.2
<b>Building</b>	“Cowshed” exterior			“Cowshed” interior		
<b>Points (MM)</b>	10.3	0.94	1.78	N/A	N/A	N/A
<b>Size (MB)</b>	271.4	73.1	26.0	N/A	N/A	N/A

#### 4.2.4 Challenges and Lessons Learned

The challenges faced during the 3D surveying phase and what lessons were learned from the attempt to solve them can be summarized as follows:

- *Weather conditions*: To properly capture the texture of the building, good weather conditions are required. If the weather provides blue skies and sunny conditions, then there will be shade on the textures, which is undesirable. If it is raining or snowing, the weather condition will be encoded in the texture. The perfect conditions for surveying the buildings occurred when it was overcast with good light. This provided the best texture throughout the building, with no inconsistencies.
- *Lighting conditions*: Scanning the interior of the buildings did not depend on weather conditions, but they proved to have a similar challenge associated with their tex-

tures. Lights coming from doors and windows will interfere with the texture and make some regions brighter than others. This can be remedied by scanning in the evening, but this requires an external ambient light source to evenly light the interior of the building. The approach adopted for this case study was to cover windows while scanning, as the buildings could not be accessed at night.

- *Detecting windows*: The “cowshed” had two glass windows that the application could not properly detect. This is due to the LiDAR using lights to detect ranges and the windows reflecting light. To avoid this issue, an image can be taken of the windows and manually added to the model in post-processing.
- *Detecting sod roof*: As is apparent in Figure 4.2, the roof was unable to be properly scanned by the surveying applications. Many Norwegian CH buildings have sod roofs, and vegetation covers most or all of them. LiDAR seems to have an issue with detecting and accurately representing vegetation for reasons that are unknown. This meant that the roof had to be manually modelled from images of the buildings.

### 4.3 Creating the Model

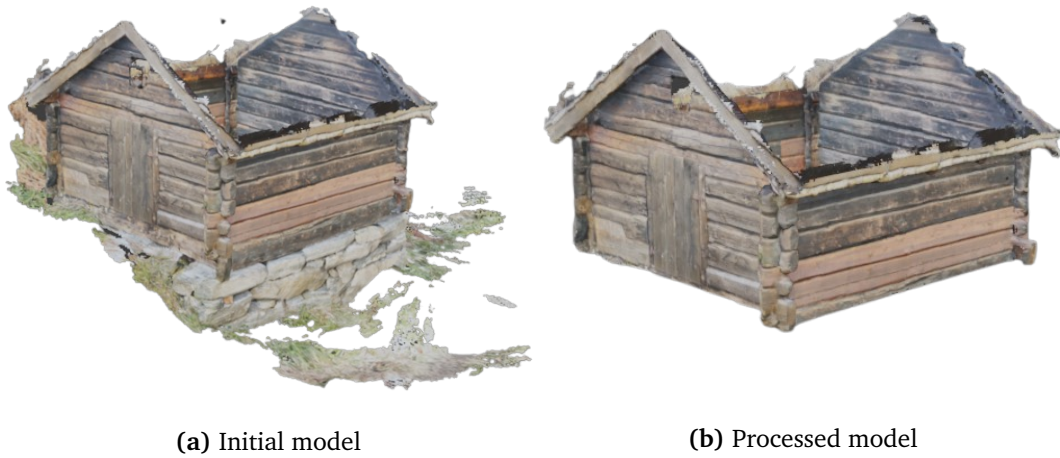
As it was only possible to acquire the point cloud for the exterior of the “cow shed” building, it was omitted from the rest of the pipeline. This was due to the original purpose of the final AR application, which was to allow the user to explore both the interior and exterior of the building. For this reason, the “drying room” is the only building that was completely modelled in this stage. The model was divided into three parts: interior, exterior, and roof. As the roof was not included properly in the scans, it had to be generated manually on the basis of the images.

#### 4.3.1 Mesh Generation and Cleanup

Each of the applications used provided a function to generate a mesh from the point clouds, which was used for the best scan clouds of the interior and exterior of the building. Each application provided several options for the processing of the models, which were: *speed* (shortest possible time to generate mesh), *space* (smallest possible size of the resulting file), *object* (best possible representation of the object), and *custom* (where the user could select different parameters used in the generation). The *object* mode was selected in each application and the resulting models were exported as .FBX files and stored in iCloud. They were then imported into Blender,<sup>1</sup> which was used throughout the 3D modelling stage as it offers an extensive number of modelling features, is free and open-source, and offers extensive resources for learning that benefit non-experts. The pipeline cleanup step was carried out by manually removing all unwanted geometry from the model. This was mainly the landscape surrounding the building, but also included the mesh generated for the roof and inside the building. Finally, the “Delete Loose” feature in Blender was used to remove vertices that were not connected to any faces or parts of the mesh.

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<sup>1</sup><https://www.blender.org/> (As of June 2022).



**Figure 4.3:** Model generation: (a) initial model generated from 3D Scanner App, and (b) processed model to remove the landscape and other unwanted geometry.

**Table 4.2:** Comparison of the 3D model specifications by application. where *Poly* = Polycam, *3D* = 3D Scanner App, and *Scan* = Scaniverse

Model	Exterior			Interior		
	Poly	3D	Scan	Poly	3D	Scan
<b>Quality</b>	Good	Mediocre	Mediocre	Good	Good	Mediocre
<b>Size</b>	28.4 MB	12.3 MB	17.3 MB	3.1 MB	5.8 MB	14.2 MB
<b>Ver<sub>1</sub></b>	292 779	204 236	88 417	13 206	106 800	78 049
<b>Pol<sub>1</sub></b>	516 251	309 206	130 272	24 604	177 976	139 707
<b>Ver<sub>2</sub></b>	179 871	97 227	46 013	11 796	96 561	67 342
<b>Pol<sub>2</sub></b>	320 653	154 644	66 171	21 988	161 561	126 221
<b>Removal</b>	38%	54%	49%	11%	10%	11%

To determine which models (one interior and one exterior) to use for the remainder of the pipeline, all generated models were compared on a host of different metrics, with *quality* being the first. It was visually evaluated and considered aspects, such as texture quality, LOD, and shape (if the model was similar to the physical building, has holes, etc.) with a spectrum of five values (Terrible, Bad, Mediocre, Good, and Excellent). *Size* is the second metric; it refers to the value of which is the size of the imported .FBX file in Megabyte. *Ver<sub>1</sub>* and *Pol<sub>1</sub>* refer to the number of vertices and polygons in the initial model (shown in Figure 4.3a), with *Ver<sub>2</sub>* and *Pol<sub>2</sub>* refers to the number of vertices and polygons after the cleaning process (shown in Figure 4.3b). The final metric for comparison is *Removal*, which refers to the percentage of the initial model that needed to be removed to leave only the building (the value is the average between the percentage of vertices and polygons removed). This gives an indication of the amount of superfluous data each application recorded in the scanning process.

As Table 4.2 shows, there is a great variation between the model specifications for the exterior and interior of the building. Regarding the exterior model, the Polycam

model was selected for further development, as it was the highest quality and contained fewer texture misalignments and holes in the mesh. Although it was the model with the largest size and the highest number of vertices ( $ver_{1,2}$ ) and polygons ( $pol_{1,2}$ ), simplifying the mesh in step 7 of the pipeline will bring these numbers into the desired range. The interior model from the Polycam app was also selected for further development, as it had the joint highest quality and much lower values for size, vertices ( $ver_{1,2}$ ) and polygons ( $pol_{1,2}$ ). Polycam was also the application with the average lowest removal rate for both models, indicating higher efficiency than the others.

### 4.3.2 Model Simplification

To be effectively rendered in a visualization platform, the exterior model needed to be simplified to reduce the number of vertices and polygons contained. According to the technical specifications of Spark AR Studio,<sup>2</sup> the target software for the model, an object should not exceed 20,000 vertices or 50,000 polygons. This meant that the exterior model had to be reduced by more than 90% (the initial polygon count was 516 251 for the model). The model decimation was done inside Blender, using the *Decimate Modifier* tool. This tool requires a parameter *ratio* between 0 and 1, which indicates the total number of edges the decimated model should keep from the original. The decimation was performed on the cleaned model (shown in Figure 4.3b), which had a total of 320,663 polygons. After applying the decimation tool, the model had 19,238 polygons, reducing the target model by approximately 94%.

Decimating the model resulted in some irregularities in the mesh, such as holes and overlapping edges, that needed to be fixed. This was done in Blender, using tools that automatically merged nodes closely located vertices, deleting overlapping edges, and manually adding faces where there were holes. This manual post-processing only decreased the polygon count by 260, but removed over 6740 vertices. The entire cleaning and simplification process (steps reduced the counts of vertices and polygons by 96%, satisfying the performance requirements and recommendations of the Spark AR Studio platform.

### 4.3.3 Texture and Normal Baking

After the model cleaning process, the texture of the model contained several digital artifacts (unwanted alterations in the texture) that made the low-poly model look unrealistic. This was due to the change in the mesh structure from the decimation process and the new faces added to fill the holes. Also, the decimation removed a lot of details that the high-poly model included because of the simplification of the mesh and removal of vertices that represented features such as subtle changes in surface height. To combat these issues, the texture and normal baking process was applied to the model.

The first step in this process was to UV unwrap the model, which is the process of creating a 2D image of the mesh so that it can be textured. UV unwrapping creates a 2D

---

<sup>2</sup><https://sparkar.facebook.com/ar-studio/learn/articles/fundamentals/technical-guidelines/> (As of June 2022).

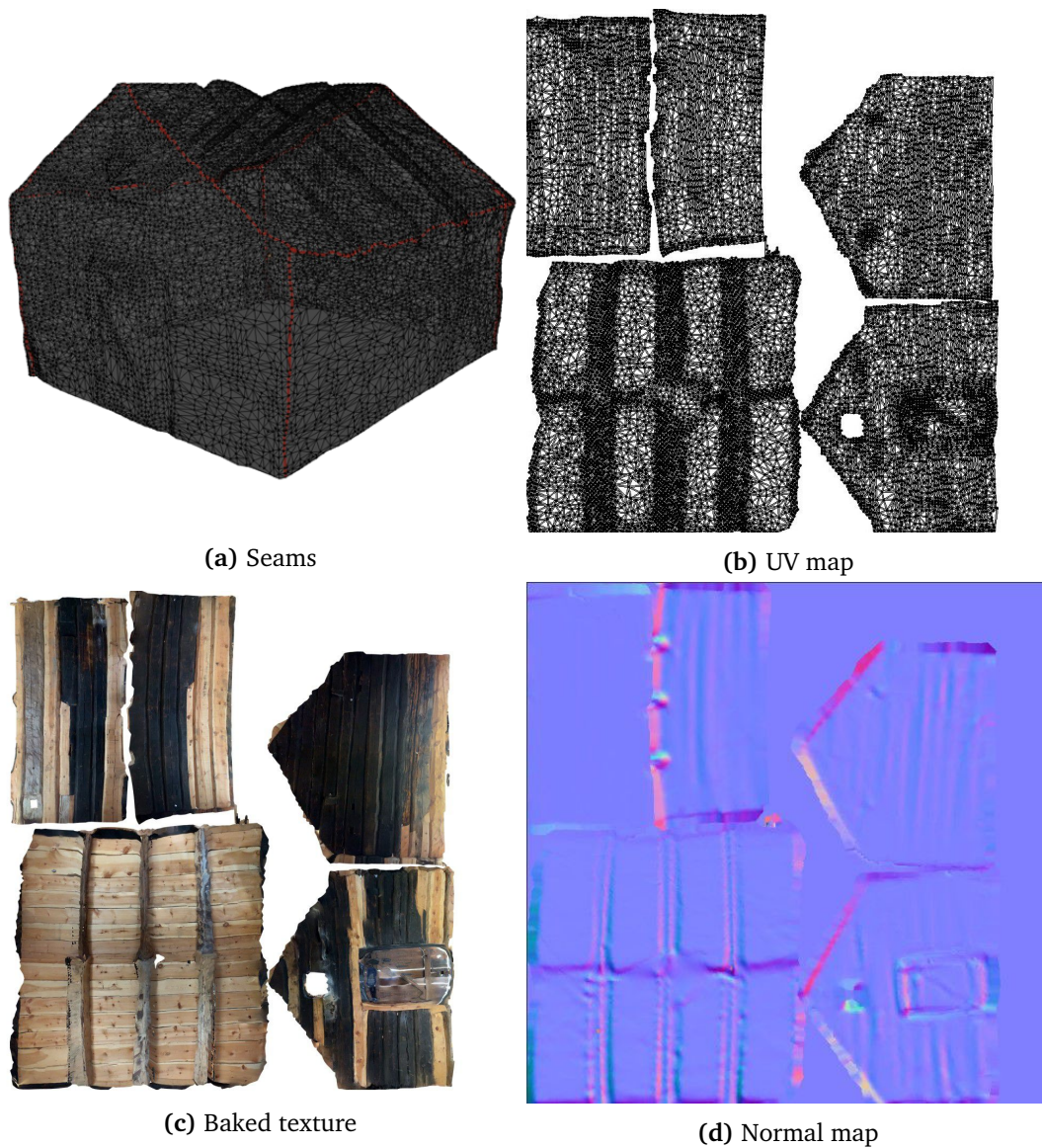
UV map, which can be used to apply the 2D texture to the 3D model. This was done on the interior model by marking seams on each of the walls and the roof (see Figure 4.4a), which divided the mesh into five sections of similar size (see Figure 4.4b). Baking was done in two separate steps, using the 'Bake' tool in Blender. First, the texture from the high-poly original model was baked onto the low-poly model, with the 'Bake Mode' parameter set to 'Diffuse,' transferring only the diffuse color information of the input model onto the target. This resulted in a 2D texture map for the low-poly model (shown in Figure 4.4c). To apply the texture to the model, an 'Image Texture' node needed to be added in the model's 'Shading' tab, where the generated texture was selected and its 'Color' output was connected to the 'Color' input field in the model. Second, normal information was transferred to the low-poly model, where the 'Bake Mode' parameter was set to 'Normal,' resulting in the normal map shown in Figure 4.4d. An 'Image Texture' was added to the shading tab, selecting the normal texture and setting the 'Color Space' parameter to 'Non Color.' The 'Color' output was then linked to a 'Normal Map' node, which was then connected to the object's 'Normal' input.

The baking process adds depth and detailed texture information to the low-poly model, making it more realistic while still keeping a low polygon count. After the baking was done on both models, they were merged together with the roof model into one complete model that included the interior and exterior models. The merged model had a complete vertex and polygon count of 13 090 and 21 041, respectively, well within the recommended range for Spark AR Studio. The model was then exported into a .FBX file format and uploaded to iCloud, where it could be stored and accessed for the next step of the pipeline.

#### 4.3.4 Challenges

The main challenge related to the modelling stage was the arduous nature of the work. Although there are tools to automatically fill artifacts, such as holes and overlapping edges, they proved to be insufficient in this case. Fixing these artifacts manually was strenuous and time-consuming. Other challenges included:

- *Hardware insufficiency:* The computer used for the modeling did not have a powerful enough GPU (NVIDIA GeForce MX150) to efficiently model the building, making the process more time-consuming than necessary. The texture baking process was the most demanding, taking more than two hours to finish for the interior model. It is recommended to have at least a NVIDIA GeForce 10 Series graphics card for the baking processes.
- *Misaligned texture:* As a result of the decimation and texture baking processes, the texture was misaligned with the geometry of the building, placing the texture of the roof edge on some of the walls (which can be seen in Figure 4.5). This might be due to a shortening of the roof edge lengths in the decimation process or a suboptimal UV map of the roof. Several different baking operations were conducted in an attempt to correct the issue, none of which proved successful.
- *Microscopic holes:* On careful inspection, there are still minuscule holes in the final model mesh. These are barely perceptible, but will dampen the level of immersion.



**Figure 4.4:** The baking process: (a) seams used in the UV unwrap, (b) the resulting UV map, (c) texture result from baking, and (d) normal map result from baking.

of the user in the AR experience. One possible solution is to *retopologize* the mesh using a tool like MeshLab or Instant Meshes<sup>3</sup> (outlined in [9]), which converts the object into a mesh using quadrilateral polygons.

<sup>3</sup><https://github.com/wjakob/instant-meshes> (As of June 2022).



**Figure 4.5:** The finalized model used for the immersive experience.

## 4.4 Augmented Reality Experience

In this case study, AR was selected as the technology to experience the CH building. This was due to its ability to superimpose virtual objects onto the physical world, allowing the building to be explored while placed at its original location. As the modelled building no longer is placed in its original location, this would allow users to travel to Ørskog and place the building where it once stood. Moreover, it was decided to use a mobile phone as the device to display the experience, due to its accessibility and frequent use of AR in the context of CH.

The platform selected to develop the AR experience was Spark AR Studio, Meta's own software to create AR experiences and post them on their social media platforms (Facebook and Instagram). It offers project templates and asset libraries that are mostly used to create AR filters, but offer functionality to interact with the physical world, like plane trackers. Spark AR Studio was selected for this case study due to the lack of research on its use in the literature. Furthermore, the software offers effortless publishing to Meta's social media platforms, which will increase its accessibility and eliminate the need to download a separate app to experience it. Furthermore, Spark AR Studio is one of the platforms Meta will be using to create content for the upcoming Metaverse, the possibilities of which will be described in Chapter 5. It also has a Blender plug-in that can be used to decimate models automatically, making them ready for importation into the software, which can be helpful for non-experts not familiar with model processing. Additionally, it offers a visual scripting system that non-experts can use to implement their desired functionality in the experience.

### 4.4.1 Experience Functionality and Scene

The main functionality of the experience is the ability to place the building model on the terrain and explore it. When the experience starts, the phone's orientation decides

where the building is placed on the terrain. If the center of the phone's screen points at a tracked plane, then the building will be rendered there (shown in Figure 4.6a). When the user taps on the building, it is placed at its current location, and the phone orientation will no longer move it. When the model has been placed, a set of buttons appears on the right side of the screen (see Figure 4.6b). When the top button is clicked, the building can be moved to a new location. If the second button is clicked, the building can be rotated. The last button allows the user to scale the building, making it smaller or larger. Moreover, the building can be explored physically when it is placed by moving towards and around the area where the building is placed. As the phone moves inside the walls of the exterior model, it shows the interior model (see Figure 4.6c).

Creating the scene was simple as there was no need to model any terrain. The developed model was imported into the software and dragged into the scene. A 'Plane Tracker' element was added to the scene so that the placement functionality could be possible. A 'Canvas' was also added to the scene, so the application could display buttons to the user for their input.

The purpose of the experience was *exploration*, as the building could be explored and manipulated both internally and externally by the user. Moreover, there is also a *preservation* aspect to the experience, as allowing exploration of the interior of this building could substitute exploration of the physical building internally, which could help slow its degeneration.

#### 4.4.2 Implementing Functionality

The functionality was implemented using a combination of a script and the visual scripting system in Spark AR Studio called the 'Patch Editor.' The script was written in JavaScript and is mainly used to track the camera's location and enable moving, scaling, and rotating operations. The main functionality of the script was to place the building on the terrain if the camera was pointing at a tracked plane (a flat surface recognized by the 'Plane Tracker' module). This was done by monitoring the movement of the camera and running the `performHitTest` function in the 'Plane Tracker' module every time the camera orientation changed. This function checks if a ray sent from a specific screen position in the direction the camera is pointing at intersects a tracked plane. If the camera is pointed at a tracked plane, the building would be rendered at that specific point (using the `trackPoint` function); if not, then the building will be hidden from the scene. The main lines of code involved in this functionality can be seen in Figure 4.7.

The Patch Editor was mainly used to recognize and respond to touch gestures, as they were easy to detect and respond to using this form of scripting. One example of this (highlighted in Figure 4.8) is if the user has clicked the scale button, then the 'Screen Pinch' node in the patch editor will be enabled and output a number based on the user pinch on the screen. The output is connected to a 'Pack' node, packing the number into a larger vector, which is connected to the 3D scaling of the building model, thus making it bigger or smaller based on the screen pinch. Additionally, the Patch Editor was tasked with showing the appropriate instructions on the screen based on which 'mode' the application was in (rotate mode, scale mode, move mode etc.).





**Figure 4.6:** The developed AR experience shown in Spark AR Player: (a) the building rendered on terrain, (b) the functionality buttons on the right side, and (c) exploring the interior of the building.

```

planeTracker.performHitTest(screenX, screenY).then((hit) => {
  if (hit) {
    building.hidden = false;
    planeTracker.trackPoint(screenX, screenY);
  } else {
    building.hidden = true;
  }
});

```

**Figure 4.7:** Code snippet of building placement functionality.

One key advantage to using both forms of scripting was the ability for them to interact, sending variables between each other. This allowed complex calculations that are difficult to script in the 'Patch Editor' to be scripted using code, then passed to the 'Patch Editor' for further use. One example where this was used was to send information about the device, like screen size and camera orientation, from the 'Patch Editor' to the script file. Finding these variables using code was difficult, while in the 'Patch Editor'

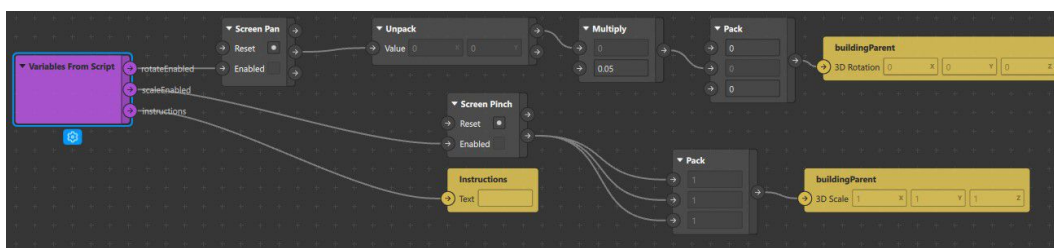


Figure 4.8: Patch Editor example.

there was a dedicated node (or patch) that provided both pieces of information. To send variables between the two scripts, one had to add a variable in the ‘From Script’ or ‘To Script’ tabs after selecting the script file in the ‘Assets’ view. After being declared, they could be accessed by code (`Patches.outputs.getVariable(variableName)`) or patch (the purple node seen in Figure 4.8).

The experience was tested and debugged using the ‘Spark AR Player’ application for the iPhone. This made testing very simple, as the phone only had to be connected to the development computer by USB and the application downloaded. The experience could then be sent to the device easily by clicking the ‘Test button on the device’ and selecting the phone. This published the experience on the ‘Spark AR Player’ app where the newly implemented functionality or code could be tested. Moreover, the debug log from the application could be seen on the development computer, allowing for seamless debugging between the phone and the computer.

#### 4.4.3 Publishing the Experience

Publishing an experience directly onto Instagram and Facebook is easily done by clicking the ‘Publish’ button in Spark AR Studio. A modal window will pop-up and ask for information about the experience and which platforms they are intended for (Instagram, Facebook, or both). The experience will be compressed and the file size for each type of device (iOS, Android or Older Android) need to fulfill the size requirements of the intended platforms, with Instagram having a size limit of 4 MB while Facebook has 10 MB. If the requirements are met, the experience is sent to the ‘Spark AR Hub’ where the audience of the experience is selected, offering the options to make it a ‘Public’ (anyone on the platform get access) or ‘Link only’ (only people with a share link get access). Publishing the experience online was left for future work.

#### 4.4.4 Challenges

Here are some of the challenges faced in developing the AR experience using Spark AR Studio:

- *Lack of online resources:* The main challenge in development was the lack of resources from Spark AR Studio that could be found online. As it is a relatively new tool (launched in 2017) and is mostly used for creating filters, there was a lim-

ited amount of content on the challenges faced when placing and exploring a 3D model. In software development, forums and other channels where developers can post issues and comment on possible solutions are very useful. Trying to solve a whole new problem on your own is like shooting in the dark.

- *Building drift*: One of the main challenge was that the building drifted after it was placed on the terrain. Initially, the position of the building was set in the script, and as the user moved to explore the building, it moved on the terrain. Correcting the issue required the building to be a child of the 'Plane Tracker' and set the position of the tracked point instead of the building. This anchored the building to a point in the physical universe that did not move as the device moved.
- *Low size limits*: The size requirements for publishing were initially too low for the experience to be published for all devices. The compressed experience file did not meet the Instagram size limit for older Android devices. To solve this, the project needed to be altered to allow publication on these devices, limiting the amount of features and secondary data that could be added.

## Chapter 5

# Immersive Virtual Heritage Experiences in the Metaverse

This chapter will outline the possibilities for IVHE in the Metaverse. First, it will outline some proposed features based on Meta's vision of this virtual world and how these can be leveraged to support CH and the creation of IVHE. Lastly, some of the challenges related to the implementation of the Metaverse will be described.

### 5.1 Meta's Metaverse vision

*The next platform and medium will be even more immersive, an embodied internet where you're in the experience, not just looking at it, and we call this the metaverse.*  
- Mark Zuckerberg, *Meta Connect 2021*

The latest and most exciting development in the realm of immersive technology is the proposed introduction of the Metaverse. One of the first companies to outline their vision for the Metaverse was Meta, who dedicated their entire 2021 keynote, *Meta Connect 2021* [8], to describing how they intended to implement this virtual world. Mark Zuckerberg<sup>1</sup> revealed that it was already under development and that some of the fundamental building blocks needed to create the space were already in place. The keynote explored all the possibilities the Metaverse had for social interaction, remote work, gaming, fitness, entertainment, education, and more. Moreover, some key challenges related to privacy, devices, and immersion were discussed. As this keynote is the most detailed and extensive prediction of how the Metaverse will manifest, it will be used to explore the possibilities of its use in CH.

#### 5.1.1 Building Cultural Heritage Public Rooms

*There are going to be all kinds of different spaces that people make ... Whole worlds that you can teleport in and out of whenever you want.*  
- Mark Zuckerberg, *Meta Connect 2021*

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<sup>1</sup><https://www.britannica.com/biography/Mark-Zuckerberg> (As of June 2022).

One of the prospects of the Metaverse outlined in the keynote, was the ability of anyone to create and design public rooms that other users could access. The Metaverse is not something Meta will be able to do on their own, it will require creators from all over the world to develop experiences and worlds that others can enjoy, much like groups or pages on Facebook are created and managed by the users. This could be leveraged by museums and other CH foundations to create virtual museums or entire worlds that contain their 3D reconstructed artifacts, monuments, exhibits, and buildings as public rooms for anyone to visit. One example of a possible CH public room is the virtual museum developed by Banfi et al. [26], where users could visit their 3D reconstructed model of the Arco della Pace and see interactive exhibits of the historic development of the monuments. These public spaces could include interactive games and activities that educate visitors about the significance and history of their CH, as the gamification of CH has been shown to increase interest, especially in young people [1]. Additionally, they could allow interaction with fragile CH objects which would feel realistic and immersive, an aspect of the Metaverse which was outlined in the keynote.

From a user perspective, these kinds of public CH spaces in the Metaverse could allow people from all over the world to access and learn about CH that would have been logistically difficult to experience in the real world. A user in Asia could visit and explore the “cow shed” from Fiskå by tapping into the Metaverse and teleporting to the Sunnmøre museum public room where the building is on exhibit. Moreover, this could allow people to socially explore CH together regardless of their physical locations in the world. Two friends located in Argentina and Sweden respectively, could access and explore the 3D reconstructed Eiffel tower together without exiting their homes. Additionally, this could increase the appreciation for and exposure of different kinds of CH from different cultures and end racism.

### 5.1.2 Selling Digital Goods

***Businesses will be creators too, building out digital spaces or even digital worlds. They'll sell both physical and digital goods as well as experiences and services.***

- Mark Zuckerberg, *Meta Connect 2021*

As the Metaverse will be built by the users, their efforts should not go unrewarded. Meta discussed the desire to create a Metaverse economy in which creators will be compensated for their efforts to help bring content and experiences into the space. This can be leveraged by CH institutions to sell their 3D reconstructed objects to regain their initial investments in the development of the objects, spaces and experiences. Creating IVHE requires investments in equipment, implementation, and time for CH institutions regardless of their technical decisions. Having the opportunity to monetize their efforts in the Metaverse could create powerful incentives for creating more IVHE experiences, in turn 3D reconstructing many valuable CH objects and sites. This could also help the institutions raise funds for conservation of their physical assets. Studies have already shown the potential of using NFTs (Non-Fungible Token) as a way to raise funds for the preservation of CH [80].

For the user this could allow more interaction and ownership of their CH. 3D re-

constructions of clothes with CH significance could be bought and used for the users avatar, virtual CH objects like vases or statues could be bought and exhibited in the user's own rooms or home spaces, and VH buildings or landscapes could be bought to use for home spaces. This could in turn increase the accessibility and exposure of CH, increasing user interest and willingness to visit both the virtual and physical locations of the reconstructed objects.

### 5.1.3 Placing Virtual Objects at Physical Locations

*We're building tools that creators can use to place digital objects into the physical world and let people interact with them. ... Tools like Spatial anchors and scene understanding capabilities will help make these mixed reality experiences feel seamless.*

- Mark Zuckerberg, *Meta Connect 2021*

The Metaverse is not only a purely virtual space, it will be possible to merge the physical and virtual worlds using the immersive technologies, mainly AR and MR. Meta are already working on AR smart glasses that have the same ability of devices like HoloLens, to realistically superimpose virtual objects into the physical world. If such a seamless and realistic integration of the physical and virtual worlds is made possible, CH institutions can leverage it by placing their virtual objects in their original locations so people can explore them. Many protected artifacts or monuments have been physically moved to museums or other protected places for preservation purposes, removing them from their natural habitat. Virtually reconstructing them can allow these objects to be reintroduced into their original locations and explored where they once stood. Moreover, many CH sites and objects that have been damaged or lost over time can be reconstructed and reimposed into their original locations.

If this was to materialize, the Metaverse user could be able to travel to historic sites that have been modified or damaged over time and still explore them as if they were still intact. Either by phone or smart glasses, the removed or damaged objects could be realistically superimposed into the landscape and explored as if they were physically there. This could be leveraged in the case study outlined in Chapter 4, in which both the relocated buildings could be superimposed into their original locations and users could explore them, both externally and internally, at their historic sites.

## 5.2 Challenges

As exciting as these possibilities are, they are still a few years from being properly implemented. There are still a "dozen technological breakthroughs" [8] that need to happen before the Metaverse will reach the outlined vision of Meta. Some of the key challenges that need to be solved in order to reach this vision, and make the Metaverse as immersive as the real world, include:

- *Technological*: The main challenge is technological in nature, as many of the envisioned features require a high level of immersion that is not possible today. The

keynote outlined five main areas where there would need to be technological advancement: *display* (smart glasses), *audio* (realistic 3D audio), *haptics* (ability to realistically touch objects), *hand tracking* (recognizing gestures and movement), *eye tracking* (place objects where the user is watching), and *Mixed Reality* (virtual objects interacting with physical surroundings) [8]. Research is being conducted in each of these fields, but solving these technological challenges will require patience and investment.

- *Implementation*: Although some of the envisioned features are already in Beta, a lot of the mentioned features are a long way from being implemented. Building a platform that will support the creation, storage and experience of thousands of virtual worlds will be demanding. Meta also proposed their wish to include interoperability in the Metaverse, allowing avatars, models and experiences to be accessed across platforms, which requires careful planning and collaboration between corporations.
- *Privacy*: As this technology has a potential to be very intrusive and can collect data on many intimate details, privacy is a major challenge when developing the Metaverse. The sophisticated sensors needed for completely immersive experiences will collect a lot of sensitive data that need to be properly secured.

## Chapter 6

# Conclusions

This chapter will describe the conclusions of the thesis, outlining the contributions derived from the attempt to address the research questions, some closing remarks, and possible venues for future work.

### 6.1 Contributions

The objective of this thesis was to explore and encourage the use of 3D reconstruction and immersive technologies in the context of CH. To address this objective, two research questions were formulated and explored throughout the report.

**RQ<sub>1</sub>**: How can immersive experiences in eXtended Reality be leveraged to preserve, disseminate, and promote Cultural Heritage?

The first research question (**RQ<sub>1</sub>**) was addressed using the literature review provided in Section 2.2, which was related to the objective to explore how immersive experiences was implemented in other research, focusing on three aspects: *existing frameworks*, *3D reconstruction*, and *immersive technology*. The findings of the review will be used as the basis for drawing conclusions about how immersive experiences can be used for *preservation*, *dissemination*, and *promotion* of CH.

The introduction of 3D reconstruction and immersive technologies into the field of CH has given a new dimension to the concept of *preservation*. This new dimension can be considered as *virtual preservation*, where a virtual copy of the CH object is created and preserved in the virtual space. By creating this virtual copy through 3D reconstruction, an accurate representation of its current condition can be documented and forever accessible in digital form. Moreover, such models can be used to guide restoration work for historic artifacts, structures, and environments, where parametric HBIM models can be created for analysis and conservation [39]. However, there are some cases where it is not economically feasible to continue conservation efforts and stop the gradual degeneration of a CH object. In such cases, 3D reconstruction could be used to document the object and save it for possible later reconstruction [5]. Furthermore, this could prove crucial in preserving CH that is particularly susceptible to natural disasters such as storms, earthquakes, landslides, etc. [81]. Having accurate 3D models of these objects can al-



low them to be accessed even after they are lost, allowing them to be explored either by superimposing them back into the physical world using AR/MR or by creating a virtual environment in VR.

Another aspect of CH is the ability to communicate its significance and history to the general public, also called *dissemination*. This aspect is becoming increasingly difficult for CH institutions to keep up with, especially with respect to younger generations [1]. Immersive experiences offer the opportunity to disseminate CH to people who are not present on the site, eliminating the need to be physically present to explore it. However, actually displaying the artifact is only one part of dissemination, and explaining its relating information, such as context, significance, and history, is another. Immersive technologies can also be beneficial in this regard, as they have the ability to add new layers to reality. Instead of a simple information plaque or audio narration, XR can show animations, related models, and outline the hidden meanings in CH, as demonstrated by the AR app developed for cave paintings described by Choudary et al. [55]. Education is an important aspect in the dissemination of CH, and XR has already been shown to improve learning at CH sites by allowing for a more interactive and personalized learning experience [49, 59]. Moreover, XR offers the possibility of gamification at CH sites, creating interactive educational games that involve CH to make it easier to digest, especially for young people [1].

Promotion is also a crucial aspect in CH, as it helps attract visitors to the physical location of the sites. This generates revenue for CH institutions and provides an opportunity to disseminate its importance to a larger audience. New technologies have shown benefits in the promotion of CH by providing interactive and online access, creating new opportunities to reach and discover new audiences [82]. Immersive experiences can allow CH institutions to showcase their objects outside the confines of their physical locations, enticing people to visit and experience the objects in real life. There are several avenues where CH institutions can publish their experiences and gain more exposure to their objects and exhibitions. Common VR marketplaces and the introduction of XR in social media can allow anyone with a VR headset or social media profile to access immersive CH experiences, which could help promote exhibitions as both social media and VR can be used effectively to visually promote audience development and engagement in CH services [83]. Furthermore, people with greater technological interest could be more inclined to visit CH sites if they knew that immersive technologies were being used in exhibitions, as research has shown the epistemic benefits of using XR for CH [59].

Although the Metaverse is still some years away, it has significant implications for the accessibility of immersive technologies in everyday life. If it is really the successor to the Internet, then its reach and impact will affect most people living in society. Therefore, the public will have better access to immersive experiences of CH developed for the Metaverse. These experiences will be available at all hours, unlike the exhibitions at museums and other CH institutions, and they can be accessed along with friends. Moreover, the Metaverse might provide a permanent virtual home for CH objects that have perished or are doomed to perish, such as some of the CH buildings of Norway [7]. 3D reconstructing the most vulnerable of these buildings could preserve their CH and allow them to be superimposed back into their original locations using AR. This could aid

in their preservation and ensure that they can live a virtual existence after their physical forms have been lost.

**RQ<sub>2</sub>:** How to design, implement, and validate a generic pipeline to create virtual Cultural Heritage content and present it in immersive experiences?

The second research question (**RQ<sub>2</sub>**) was related to the objective of encouraging the use of immersive experiences in the context of CH. It was addressed by designing the steps of a generic pipeline to create these experiences and validating it through a case study. The proposed Immersive Virtual Heritage Experience (IVHE) pipeline outlines the process of creating immersive CH experiences in XR. It provides a generic workflow that can work with any type of technical decision and is suitable for non-experts as it avoids specialized models and tools. However, it is possible to extend the pipeline with additional steps in the *Modelling* stage to add specialized models, such as HBIM or NURBS. As the pipeline is generic and non-specific to any technical decisions, it does not offer detailed guidance on how to complete each step, rather outlining the overlying steps needed in the process. For this reason, the proposed pipeline can be viewed as a starting point for the creation of an immersive experience, where an additional search must be conducted for a specific technique, tool, or application.

Providing a generic pipeline for XR experiences is difficult, as the field does not have established standards. Each platform, technique, and tool requires a specific pipeline that is customized for its use, resulting in a wide variety of steps and processes. Although the first two stages of the pipeline (*Surveying* and *Modelling*) will vary in the steps necessary based on technical decisions, the output of each stage is generic and can be imported and edited in a variety of different tools. This is not the case with the final stage of the pipeline (*Immersive Experience*), where the output of the stage depends on the chosen platform of development. Immersive experiences created in one platform cannot be imported and edited in another. This lack of interoperability forces the developers to decide which platform to use based on desired features, display device and application, limiting its accessibility. For the pipeline to be truly generic, there is a need for established standards in the formats of immersive experiences or a tool that allows deployment on any device and platform.

The case study provides a specific implementation of the proposed pipeline in a case study, developing a mobile AR application using 3D reconstructed CH building from Ålesund, Norway. It validates the use of the pipeline and can be used by other CH institutions, such as museums, that seek to develop AR experiences that allow exploration of the interior and exterior of CH buildings. The case study used the iPhone 13 Pro and commercially available applications found on the iOS app store, which showed that expensive equipment or complex techniques are not necessary to create models of relatively high quality that can be easily imported into immersive experiences. These solutions are especially useful for non-experts, as they automatically complete several of the steps in the pipeline. However, there were issues related to the documentation of the sod roofs, which indicates that this approach is not suitable for similar CH buildings, which are common in Norway, but could be useful for buildings that do not share this feature.

The potential of a new AR platform (Spark AR Studio) to be used to develop mobile AR experiences in the context of CH is also explored. The case study indicates that this platform can be useful for promotional purposes, as it can easily post experiences on Instagram and Facebook. It might also be useful for non-experts, as the visual ‘Patch Editor’ scripting mode can allow complex features to be included without the need for experience in coding. However, the platform’s limited functionality regarding the placement and interaction of virtual models with the physical world indicates that it is not suitable for more elaborate experiences. Moreover, the platform has low maximum sizes for publishing experiences, which makes it ill-suited for complex models or experiences with large file sizes. However, this might change in the future, as the platform is intended to be used for developing Metaverse experiences.

The introduction of the Metaverse might help alleviate some current concerns and challenges in the context of creating immersive experiences of CH. One such challenge is the lack of a common standard for creating immersive VH experiences which the Metaverse might solve by creating a common destination for all such experiences. The interoperability needed for the Metaverse to import experiences from anywhere, might be the incentive needed for immersive experience platforms to create a common standard, as each will wish to make their experiences accessible to the broadest audience possible. Another possible benefit is the ability for CH institutions to monetize their immersive experiences to generate funds for restoration work on physical objects and the further development of other immersive experiences. It may also help recoup some of the initial investments needed to begin creating these experiences.

## 6.2 Future Work

Here is a list of several different ways in which this work can be extended:

- **User Study.** Publish the experience on social media platforms and conduct a user study to test whether exposure to such experiences can increase people’s interest, appreciation, and willingness to preserve CH.
- **Adding Metadata.** Some metadata on the CH buildings were collected in text form on their significance, which could be added to the models. This would further strengthen the dissemination aspect of the experience and could allow for a similar interaction with the objects. The solution would follow the ideas of Teruggi et al. [67]. In their work, textual information was provided for specific components after selection.
- **Creating HBIM Model.** The use of the methodology of Banfi et al. [33] and the creation of HBIM models of the CH buildings could be carried out to show how many additional steps would be required to include specialized models into the IVHE pipeline. Moreover, it would test the potential of using the iPhone 13 Pro and commercial applications to create HBIM models, possibly reducing the budget required for such projects.
- **Develop MR Experience.** An extension of the developed experience itself could be to use the Microsoft HoloLens to display the experience, which was done by

Rahaman et al. [10], Bekele et al. [68], and others. This would create a more immersive experience that allows for more interaction between the environment and the building.

- **PRISMA Review.** One of the limitations of the provided literature review is that it does not follow any structured methodology. Using a more systematic approach like PRISMA [84] could contribute to improving the scientific impact of insights related to the main findings, as well as to making the conducted research more reproducible.

### 6.3 Closing Remarks

Although the thesis has shown considerable benefits to using 3D reconstruction and immersive technologies in CH, these should not be used as a substitute for physical CH itself. Rather, they should be used as a complementing resource to increase awareness, accessibility, and interest in these valuable artifacts, buildings, and landscapes.

In the case of the Norwegian CH buildings, the ability to create accurate 3D models of the buildings should not be used as an excuse to stop conservation efforts and let some of them die. Having reconstructed models to display in immersive experiences should be considered as a backup plan if conservation efforts are no longer possible. They can also be used to reconstruct some of these buildings from scratch if their condition has degenerated to the point where restoration is futile.

Creating immersive experiences from these models should aim to expose the public to more CH, so that they see the value in preserving it for the coming generations. Using these new technologies and their ability to create immersive, interactive, and educational experiences can awaken a latent interest in CH for people who have not experienced it properly before.

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