School of Media, Creative Arts and Social Inquiry

Collaborative and Multi-Modal Mixed Reality for Enhancing Cultural Learning in Virtual Heritage

Mafkereseb Kassahun Bekele

This thesis is presented for the Degree of
Doctor of Philosophy
of
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To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Mafkereseb Kassahun Bekele

“*I dedicate this thesis to my father Kassahun and my wife Alem (my sunshine) who gave me unreserved love and support. I don't have enough words for you, thank you so much*”

— Mafkereseb Kassahun Bekele

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Abstract

This study explored whether collaborative and multi-modal mixed reality enhanced cultural learning in virtual heritage environments. Studies in the virtual heritage domain identify collaboration (social interaction), engagement, and contextual relationships as key elements of interaction design that influence users' experience and cultural learning in virtual heritage applications. First, the research attempted to compare the existing immersive reality technologies and interaction methods against their potential to enhance cultural learning in virtual heritage applications and identified a specific integration of collaborative and multi-modal interaction methods and mixed reality that can be applied to virtual heritage. Second, the research presented a redefinition of mixed reality from a perspective emphasising the relationship between users, virtuality, and reality as a fundamental component and attempted to answer two critical questions: (1) what mixed reality from virtual heritage perspective is and (2) whether mixed reality is just a form of immersive reality that serves as a bridge to connect the real world with a virtual one or a fusion of both that neither the real nor the virtual world would have meaning without a contextual relationship and interaction with each other. Third, the research proposed, designed, and implemented a novel approach to use maps as interaction interfaces in a mixed reality environment that could be applied to specific virtual heritage settings with a predefined cultural and historical context. The primary focus of the proposed interaction method named 'Walkable Mixed Reality Map' was to use interactive, immersive, and walkable maps to allow users to interact with cultural content, 3D models, and different multimedia content at museums and heritage sites. Following that, the research extended the 'Walkable Mixed Reality Map' to clouds-based collaborative and multi-modal mixed reality application aiming at enhancing cultural learning in virtual heritage mixed reality environment. Finally, the mixed reality application was then evaluated at the Western Australian Shipwrecks Museum by experts, archaeologists, and curators from the gallery and the Western Australian Museum. A questionnaire, semi-structured interview, and observation were used to collect data. The results suggested that integrating collaborative and multi-modal interaction methods with mixed reality technology facilitated an enhanced cultural learning in virtual heritage environment.

Publications submitted as part of this Thesis

1. **Bekele, M. K**., & Champion, E. (2019). A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage. Frontiers in Robotics and AI, 6, 91.

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3. **Bekele, M. K.** 2021. Mixed Reality: A Bridge or a Fusion Between Two Worlds? In: Champion, E. M. (ed.) Virtual Heritage: A Guide. Pp. 93–103. London: Ubiquity Press. DOI: https://doi.org/10.5334/bck.i. License: CC-BY-NC

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Six out of the seven published materials submitted as part of this Thesis by Publication were conceived, planned, and coordinated by Mafkereseb Kassahun Bekele.

I, Mafkereseb Kassahun Bekele, confirm that I am the sole author of three of the seven published materials presented in this Thesis by Publication. I confirm that I undertook the conception, design, analysis, and majority of the writing for three of the co-authored publications. I also confirm that I contributed to the conception, design, implementation, and partial writing of the publication entitled: Rahaman, H., Champion, E., & **Bekele, M**. (2019). From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience. Digital Applications in Archaeology and Cultural Heritage, 13, e00102.

Signed and detailed statements from co-authors related to co-authored publications are provided.

Signed:

DocuSigned by:
418937EB1C4D4E8...

Mafkereseb Kassahun Bekele

Date: 10/30/2021

Dr David McMeekin, Primary Supervisor

Signature: DocuSigned by: David McMeekin 7123E3BD3CF24AF...

Date: 10/31/2021

Professor Erik Champion, Co-Supervisor

Signature: DocuSigned by: C531FDDE4B9E4FC...

Date: 10/30/2021

Dr Hafizur Rahaman, Co-Supervisor

Signature: DocuSigned by: E9040EDE6E204CF...

Date: 10/31/2021

DocuSign Envelope ID: 95C939BD-8B20-4D2A-9713-30B5A0F214D3

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To Whom It May Concern

I, Mafkereseb Kassahun Bekele, contributed to the conception, design, literature review, analysis, and majority of the writing of the paper/publication entitled:

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Signature of candidate DocuSigned by: 418937EB1C4D4E8... Date: 10/30/2021

I, as co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

Erik Champion Signature: DocuSigned by: C531FDDE4B9E4FC... Date: 10/30/2021

Publication 2: Co-Author Statements

To Whom It May Concern

I, Mafkereseb Kassahun Bekele, contributed to the conception, design, literature review, analysis, and majority of the writing of the paper/publication entitled:

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Signature of candidate DocuSigned by: 418937EB1C4D4E8... Date: 10/30/2021

I, as co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

Erik Champion Signature: DocuSigned by: C531FDDE4B9E4FC... Date: 10/30/2021

DocuSign Envelope ID: 95C939BD-8B20-4D2A-9713-30B5A0F214D3

Publication 3: Author Statement

To Whom It May Concern

I, Mafkereseb Kassahun Bekele, confirm that I am the sole contributor to the conception, design, literature review, analysis and the writing of the paper/publication entitled:

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Signature of candidate — DocuSigned by: 418937EB1C4D4E8... — Date: 10/30/2021

I, as co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

Hafizur Rahaman	Signature: DocuSigned by: E9040EDE6E204CF...	Date:	10/31/2021
Erik Champion	Signature: DocuSigned by: C531FDDE4B9E4FC...	Date:	10/30/2021

DocuSign Envelope ID: 95C939BD-8B20-4D2A-9713-30B5A0F214D3

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Signature of candidate — DocuSigned by: 418937EB1C4D4E8... — Date: 10/30/2021

I, as co-author, endorse that this level of contribution by the candidate indicated above is appropriate.

Erik Champion	Signature: DocuSigned by: C531FDDE4B9E4FC...	Date:	10/30/2021
David McMeekin	Signature: DocuSigned by: David McMeekin 7123E3BD3CF24AF...	Date:	10/31/2021
Hafizur Rahaman	Signature: DocuSigned by: E9040EDE6E204CF...	Date:	10/31/2021

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Journal Publications

1. **Bekele, M. K.**, Pierdicca, R., Frontoni, E., Malinverni, E. S., & Gain, J. (2018). A survey of augmented, virtual, and mixed reality for cultural heritage. Journal on Computing and Cultural Heritage (JOCCH), 11(2), 1-36.

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1. Champion, E., **Bekele, M.** (2019). Mixable reality, Collaboration, and Evaluation. S36: Computer Applications and Quantitative Methods in Archaeology (CAA2019), Krakow, Poland, 23-27 April 2019.

2. Nishanbaev, I., Champion, E., Rahaman, H., & **Bekele, M.** (2018). Integrating 3d Models and GIS for Digital Cultural Heritage. Paper presented at the Centre for Digital Heritage meeting 2018 (CDH 2018): 3D archives, (re)use and Knowledge production, 18-19 June 2018, Lund, Sweden.

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Invited Lectures/Panels/Teaching Delivered

1. Champion, E., **Bekele, M.**, Fayad, S. (2018). Pelagios Working Group "PelagiOZ LAMLOD Workgroup Landscape Data, Art/Artefacts & Models as LOD, DownUnder (LAMLODoz)" Paper presented at the Linked Pasts IV 2018 conference, 11-13 December 2018, Mainz, Germany.

2. **Mafkereseb Bekele**, Curtin University: HoloRecogito: Integrating Recogito and Mixed Reality (via a HoloLens); 27 July 2018 https://makerspace.library.curtin.edu.au/playing-linked-open-data/

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Chapter 1

Introduction

The best way to read the thesis is to start from the introduction chapter first and read the conclusion chapter (see Chapter 9).

To avoid repetition, this chapter provides brief discussion on selected topics to underline their contribution towards establishing the theoretical background and overall research framework. Detailed discussion and literature review will be provided to specific topics throughout a series of published works included in this Thesis by Publication.

1.1 Background

Virtual Heritage (VH) is an emerging field that applies immersive reality technologies and scientific methods to Cultural Heritage (CH) to simulate, preserve, and disseminate cultural assets in a form of diverse multimedia approaches. Mixed Reality (MR) is a segment of immersive reality technology that VH utilises to disseminate cultural knowledge in a form of immersive and interactive experience (Bekele et al., 2018; Bekele and Champion, 2019a). Furthermore, studies in the domain demonstrate the important role immersive reality technologies and Human-Computer-Interaction (HCI) play in terms of enabling engaging interaction and enriching visiting experiences in museums (Addison and Gaiani, 2000;

Adhani and Rambli, 2012; Anthes et al., 2016; Katifori et al., 2018).

Mixed Reality (MR) enables user-centred and personalised presentation of VH and makes cultural heritage digitally accessible in a form of virtual reconstruction, virtual museum and exhibitions. Virtual reconstruction and representation aim at enabling users to visualise and interact with digitally reconstructed tangible and intangible heritages. Such applications allow blending historical views with their current appearance. For instance, damaged architectural assets can be virtually reconstructed at their historical location. Additional information beyond the virtual reconstruction itself can also be overlaid along with the virtual elements. MR can play an important role in the restoration of lost heritages, starting from interacting with the virtual reconstruction of statues and extending to reviving lost cultural practices in their original forms (Vlahakis et al., 2001).

Virtual museums and virtual exhibitions intend to improve visitors' experience in museums and heritage sites, typically through personalised and immersive virtual tour guidance. In general, such applications simulate and enhance museums and heritage sites including their tangible and intangible assets (Bekele et al., 2018).

MR applications are emerging in the VH domain following the recent advances such as Microsoft HoloLens (Bottino et al., 2017; Funk et al., 2017; Pollalis et al., 2017; Scott et al., 2018). For instance, Pollalis et al. (2018) present an application that utilises Microsoft HoloLens to allow object-based learning through mid-air gestural interaction with virtual representations of museum artefacts.

The success of immersive reality applications in the context of cultural learning is strongly dependent on the interaction methods they employ (Caputo et al., 2016; Tost and Economou, 2009; Economou and Pujol, 2007). Studies in the domain identify collaboration (social interaction), engaging experience, and contextual relationship as key elements of interaction design that influence users' experience and cultural learning (Carmigniani et al., 2011). Interaction methods that enable these key elements lead to enhanced cultural learning. Hence, enhancing cultural learning in immersive reality-based VH requires combining immersive reality and well-designed interaction methods to provide meaningful content with engaging, collaborative, relatable experiences.

This thesis, therefore, designs, implements, and evaluates a Collaborative and Multi-Modal MR application to achieve an enhanced cultural learning in VH environment. The rationale behind this approach is that:

1. MR has the potential to fuse virtual environments with the physical world. This allows for dissemination and presentation of digital heritage content at their natural location. Hence, users will be able to establish a contextual relationship with the real-virtual environment.

2. Collaborative interaction enables face-to-face collaboration (social interaction) and distribution of interaction tasks among users. Cultural learning is directly impacted by users' effort to interact with the system (Champion, 2006; Wang and Lindeman, 2015). Hence, Collaborative interaction enables enhanced cultural learning since interaction is shared.

3. Multi-modal interaction methods exploit multiple modes, such as gaze, speech and gesture. This enables enhanced interactivity and engagement because the interaction mimics how users interact each other.

The remainder of this chapter is structured as follows. Section 1.2 will provide an overview of immersive reality technology from VH perspective. Section 1.3 defines cultural learning and reviews some VH applications that promote cultural learning. Section 1.4 discusses and reviews interaction methods and virtual environments. Following that, Section 1.5 and Section 1.6 will provide the statement of the research problem and scope of the research, respectively. The significance of the research will be discussed in Section 1.7 This will be followed by a detailed discussion on the research framework in Section 1.8. Following that, Section 1.9 will present the cultural context used as case study in this thesis. Finally, Section 1.10 will provide the structure of the dissertation.

1.2 Immersive Reality

Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV) and Mixed Reality (MR) are specific segments of the reality-virtuality continuum. In order to avoid a repetitive appearance of 'AR/VR/AV/MR', the term 'immersive reality' will serve as a collective term representing these segments. Chapter 2 provides detailed review of these immersive reality technologies and interaction methods from cultural learning and VH perspectives. In the past, immersivity and presence have been associated with or regarded as indicators of a successful VR application due to the technological constraints that made immersivity a unique quality of VR. As a result, the applicability of such aspects has not been realised in AR and MR applications until recently. However, recent advances in Head-Mounted-Displays (HMDs) enable audio-visual immersivity in all of the segments of the reality-virtuality continuum. For instance, one of the recent HMDs "Microsoft HoloLens", which is built mainly for AR and MR experience, can also be used for VR scenarios, and is capable of audio-visual immersivity. Such technical capabilities are changing the trend of immersive reality in terms of establishing a versatile platform where any segment of the continuum can be implemented upon.

1.3 Cultural Learning and Virtual Heritage

Cultural learning in VH relates to learning about specific culture from processes, engagement, and experience in a VH environment. In a broader context, cultural learning can result from navigation or wayfinding, interpretation of cultural heritage content in a virtual environment, participating in evaluation of VH project, cultural presence in a virtual environment, and the creation of meaningful content expressing cultural value or significance in a virtual environment (Ibrahim et al., 2011). Therefore, cultural learning is implicit in any VH application theme. Cultural learning can be enhanced via effective utilisation of immersive reality technology, interaction methods and meaningful cultural content or context. Throughout this thesis, enhanced cultural learning is depicted as a product of VH environment resulting from the integration of collaboration (social interaction), an engaging experience, and contextual relationship in collaborative and multi-modal MR heritage environment.

Chapter 2 provides a comparison of immersive reality technologies and interaction methods in terms of their capability to enhance cultural learning in VH. Chapter 6 and Chapter 7 report on the design and implementation of a clouds-based collaborative and multi-modal MR application that aims at enhancing cultural learning in VH. And Chapter 8 reports the result of evaluation of the application.

1.4 Interaction in Virtual Environments

Interaction between users and the virtual content is a crucial element of any immersive visualisation environment. This is even more true for VH applications where cultural leaning is impacted by the interaction with virtual content. The common types of interaction methods are: tangible, collaborative, device-based, sensor-based, multi-modal, and hybrid interaction methods. Chapter 2 discusses and reviews these interaction methods in detail.

1.5 Statement of the Research Problem

Though cultural learning is implicit in any VH application themes, it is not commonly evaluated or reported in VH studies. The major issues of immersive reality applications in VH domain, at least from the perspective of this research's objective are the following: (1) cultural learning is often overlooked; (2) evaluation and experiments diverge from the cultural context and focus on the interactivity and immersivity of the adopted technologies; and (3) collaboration, engagement, shared experience, and contextual relationship are rare characteristics in VH.

Therefore, this research will explore the potentials of MR, collaborative interaction, and multi-modal interaction to achieve the main goal of this research, which is to enhance cultural learning in VH environments.

1.5.1 Research question and objective

This PhD research asks whether collaboration (social interaction), engaging experience, and contextual relationship in MR heritage environment enhance cultural learning in VH. To determine this, the research will design, build, and evaluate a collaborative and multi-modal MR application.

1.5.2 Research Hypothesis

VH applications lack interaction mechanisms where collaborative and multi-modal interaction methods are implemented in order to enhance users' cultural learning and engagement in VH environments while they interact with specific cultural context. In order to address such issues, the approach proposed in this research integrates meaningful cultural context, multi-modal interaction interface, and collaborative MR in VH environments. It is therefore hypothesised that:

- Collaborative and multi-modal MR will enhance cultural learning by enabling collaboration (social interaction) among users, increasing engagement, and establishing more meaningful and appropriate relationships between users and specific cultural contexts.

1.6 Scope of the Research

VH is a multidisciplinary and emerging field which benefits from other emerging domains such as 3D modelling and photogrammetry and immersive reality technologies (see Figure 1.1). Human-Computer-Interaction (HCI) is another domain VH relies on. The advances in these knowledge areas determine the research direction and the general applicability of immersive reality technologies in the VH domain. As a result, the literature in the VH domain tends to adopt or apply technologies from different domains. Figure 1.1 shows the main knowledge domains or enablers of VH. The scope of this research is, therefore, to focus on a specific segment of the enablers of VH (interaction method), that is, integrating collaborative and multi-modal interaction, and MR.

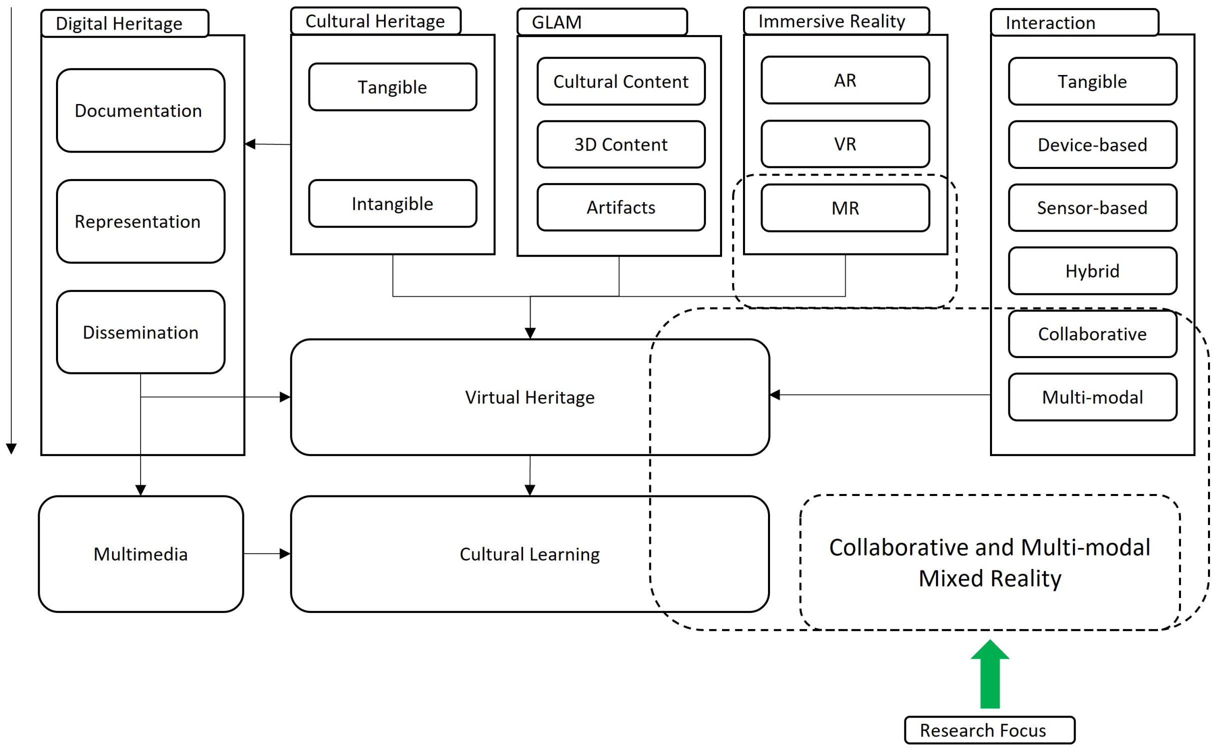

Figure 1.1: Scope of the research.

1.7 Significance of the Research

This PhD research, in a broader sense, contributes to two areas of the VH domain. There are existing theoretical frameworks in the VH domain that highlight the significance of collaboration, engagement, and contextual relationship for enhanced cultural learning. Firstly, integrating collaborative and multi-modal interaction interfaces contributes towards these theoretical frameworks. Secondly, the proposed approach could serve as an alternative to existing VH dissemination and presentation tools that the community can consider adopting to convert their digital collections into cultural learning tools.

Museums have collections of culturally significant artefacts on-site. Often, these collections are not accessible to visitors to interact with. Via immersive reality technologies, however, the artefacts can be digitally replicated and presented to visitors. The benefit of such approach is two-fold. Firstly, visitors will have a chance to interact with the digital replications of museum collections without the need to physically interact with the actual artefacts. Secondly, the possibility of being immersed in a virtual environment, where changing the form, scale, texture, and the state of those digital artefacts is possible. Such possibilities will enhance visitors' experience and engagement.

Museums are adopting immersive reality technologies as part of their regular exhibits. The most common approach among museums to date is delivering AR and VR experiences via relatively low-cost platforms such as mobile AR and cardboard VR kits. These technologies are limited in a sense that implementing immersive, interactive, and collaborative experience is technically challenging. MR technologies such as HoloLens, however, are equipped with the technological requirements for both collocated and remote collaborative and immersive experiences. This unique capability will allow museums and heritage site to create a network of a collaborative visualisation platform that enables sharing experiences among visitors from spatially distributed locations. For instance, visitors from a remote heritage site can virtually join a visiting experience taking place at a museum located somewhere else.

1.8 Research Methodology

This PhD research comprises four major phases (see Figure 1.2). The phases are briefly discussed below.

1. **Phase One (Exploring the state-of-the-art):** This research phase involves extensive literature review on the topics of immersive reality, interaction methods, virtual heritage, and cultural learning. Based on the reviewed literature, immersive reality technologies and interaction methods will be compared against their potential to enable collaboration, engagement, and contextual relationship in a VH environment.

2. **Phase Two (Establishing the conceptual base):** The outcome of phase one will establish the conceptual base for the design, implementation, and evaluation phases. This phase will introduce a redefinition of MR based on the outcome from phase one. It will also establish collaboration, engagement, and contextual relationship as key aspects of interaction design and MR experience.

3. **Phase Three (Design and implementation):** At this stage, the design and implementation of the collaborative and multi-modal MR application will take place. Before the design and development, a requirement analysis will be done following the inputs from phase one and phase two discussed above.

4. **Phase Four (Evaluation):** The last phase of the research is evaluating the collaborative and multi-modal MR application to determine its effect on cultural learning. Based on the results, this phase will provide conceptual and practical recommendations to the VH domain that professional and museums could benefit from when adopting immersive reality technologies. The evaluation will be conducted using observation, questioners, and interviews as data collection instruments.

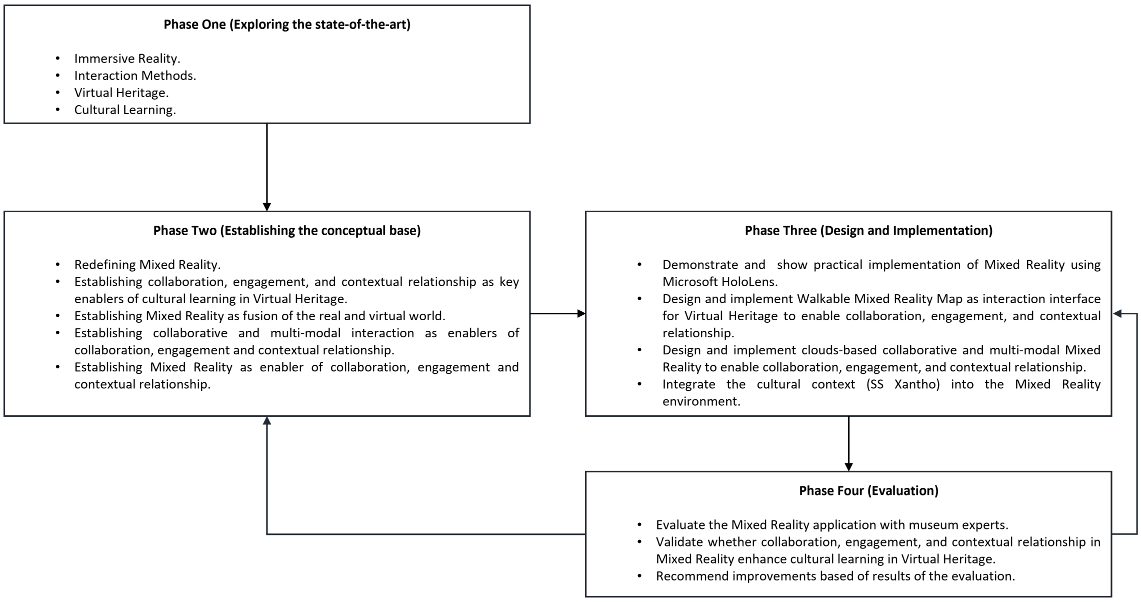

Figure 1.2: Research Framework.

1.9 Cultural Context: SS Xantho (1848–1872)

This thesis uses a specific Australian maritime history, specifically the history of SS Xantho as a case study (see Chapter 7). The significance of SS Xantho to the maritime history of Australia, Western Australia in particular, is invaluable. However, the history has not been promoted properly. Xantho has a significant place in Western Australia's maritime history and Aboriginal rock art interpretation, especially the rock paintings at Walga and Indernoona, but its significant cultural value has not received the attention and recognition it deserves.

Xantho was one of the world's first iron ships. It was built in 1848 by Denny's of Dumbarton in Scotland. In 1871, after 23 years of Scottish coastal service, Xantho was sold to Robert Stewart, who removed the old paddle wheel machinery and replaced it with a ten-year-old propeller engine built by the famous naval engineers John Penn and Sons of Greenwich. The refurbished SS Xantho was offered for sale in October 1871. In the same year, the ship was purchased and brought to Western Australia by Charles Edward Broadhurst (McCarthy, 1989). Broadhurst is also known for his entrepreneurial contributions to the state. In recognition of his contribution, a commemorative plaque has been inserted into the pavements of Perth, Broadhurst also appears in a number of short, published and private, resumes (McCarthy, 1989). In November 1879, whilst travelling to Fremantle Xantho shipped a cargo of lead ore from Port Gregory. Overloaded, its hull badly corroded and its deck planking opened by the tropical sun, Xantho began to take on water on its way down the coast. After returning to Port Gregory it struck a sandbar and sank (McCarthy, 1989).

The wreck lay forgotten until 1979 when, with the aid of local fishermen, it was located by the Maritime Archaeological Association of Western Australia, the volunteer wing of the Department of Maritime Archaeology at the Western Australian Museum. In April 1985, the engine was removed from the wreck site in the context of an excavation of the stern and then transported to a treatment tank at the Museum, in Fremantle. A schematic showing the engine in action has also been produced and it can be viewed on the engine reconstruction section of the project website.

Xantho impacted both visually and socially on indigenous groups like the Jaburrara, Martuthunira, and Ngarluma people, who lived in the hinterland of Nickol Bay. Although no European illustrations of the ship exist, there are several examples of Aboriginal rock carvings at Inthanoona Station inland from Cossack identified as the SS Xantho (see Figure 1.4). Rock art at Walga Rock is also believed to depict the vessel (see Figure 1.3).

Hence, as the primary goal of this thesis is enhancing cultural learning at heritage sites and museums, promoting the historical position of Xantho serves as a suitable cultural context for the collaborative and multi-modal MR application and its evaluation.

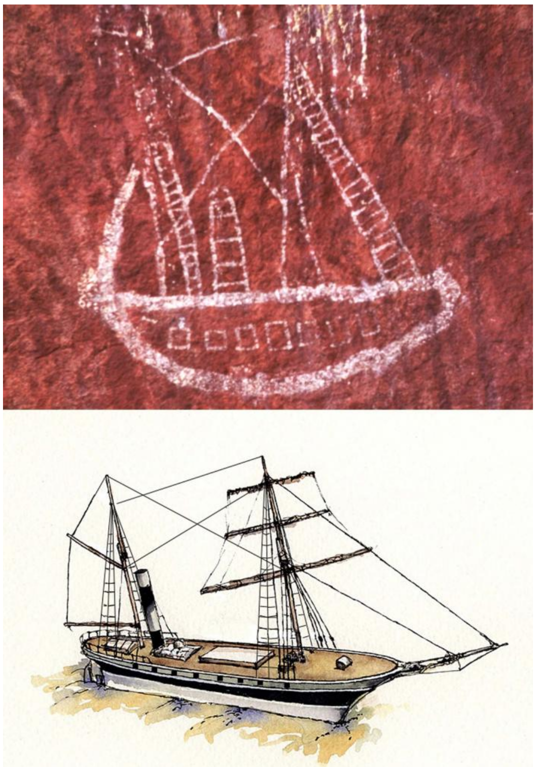

Figure 1.3: Water colour depicting Xantho with false gunports (Ian Warne) compared with the Walga Rock painting (Source: Western Australian Museum).

Figure 1.4: Rock art at Indernoona believed to show SS Xantho (Source: Western Australian Museum)

1.10 Dissertation Structure

This Thesis by Publication is structured based on the research phases discussed in Section 1.7. Figure 1.5 shows the publications that resulted from each research phase and how they connect to each other. The publications are summarised and categorised into the four research phases.

Phase 1: Exploring the state-of-the-art

1. A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage (Bekele and Champion, 2019a).
    (a) Identifies common interaction methods employed in virtual heritage and discusses immersive reality technologies in the context of cultural learning and virtual heritage.
    (b) Establishes collaboration, engagement, and contextual relationship as experiential factors the enable cultural learning in virtual heritage.
    (c) Compares various interaction methods and immersive reality technologies against their potential to enable collaboration, engagement, and contextual relationship.
    (d) Following the comparison, this study identifies hybrid interaction method (collaborative and multi-modal) and mixed reality as suitable combination to enable cultural learning in virtual heritage.

Phase 2: Establishing the conceptual base

1. Redefining Mixed Reality: User-Reality-Virtuality and Virtual Heritage Perspectives (Bekele and Champion, 2019b).
    (a) Identifies the gap in existing definitions of mixed reality from a virtual heritage perspective.

   (b) Identifies contextual relationship, that is one of the three factors to enable cultural learning in virtual heritage, as a fundamental component to redefine mixed reality.

   (c) Presents a redefinition of mixed reality from a perspective emphasising the contextual relationship between users, reality, and virtuality.

2. Mixed Reality: A Bridge or a Fusion Between Two Worlds? (Bekele, 2021b)

   (a) Based on the redefinition of mixed reality presented in the published work above, this study further explores mixed reality from a virtual heritage perspective.

   (b) Attempts to review the common depictions of mixed reality in the exiting body of literature in the context of different application themes in virtual heritage.

   (c) Establishes a boundary between augmented reality and mixed reality.

   (d) Conveys the view that mixed reality is a fusion of the real and virtual environment rather than a bridge between these worlds or a combination of properties of augmented and virtual reality.

   (e) Identifies application themes and limitations of mixed reality in the context of virtual heritage.

Phase 3: Design and implementation

1. From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience (Rahaman et al., 2019).

   (a) Provides, demonstrates, and shows practical implementations of methods to generate 3D models.

   (b) Provides workflow for deploying 3D models to Microsoft HoloLens device.

2. Walkable Mixed Reality Map as Interaction Interface for Virtual Heritage (Bekele, 2019)

    (a) Proposes and implements a novel approach to use immersive maps as interaction interfaces in a mixed reality environment applied to a specific virtual heritage setting.

3. Clouds-Based Collaborative and Multi-Modal Mixed Reality for Virtual Heritage (Bekele, 2021a)

    (a) Extends the "Walkable Mixed Reality Map" to include collaborative and multi-modal interaction methods.

    (b) Designs and implements a novel approach that integrates cloud computing, mixed reality and virtual heritage.

Phase 4: Evaluation

1. The Influence of Collaborative and Multi-modal Mixed Reality: Cultural Learning in Virtual Heritage (Bekele et al., 2021)

    (a) Evaluates the clouds-based collaborative and multi-modal mixed reality in the context of cultural learning in virtual heritage.

    (b) Based on the outcome of the evaluation, it also provides some suggestions to the wider virtual heritage community on the topics of mixed reality, interaction methods and cultural learning.

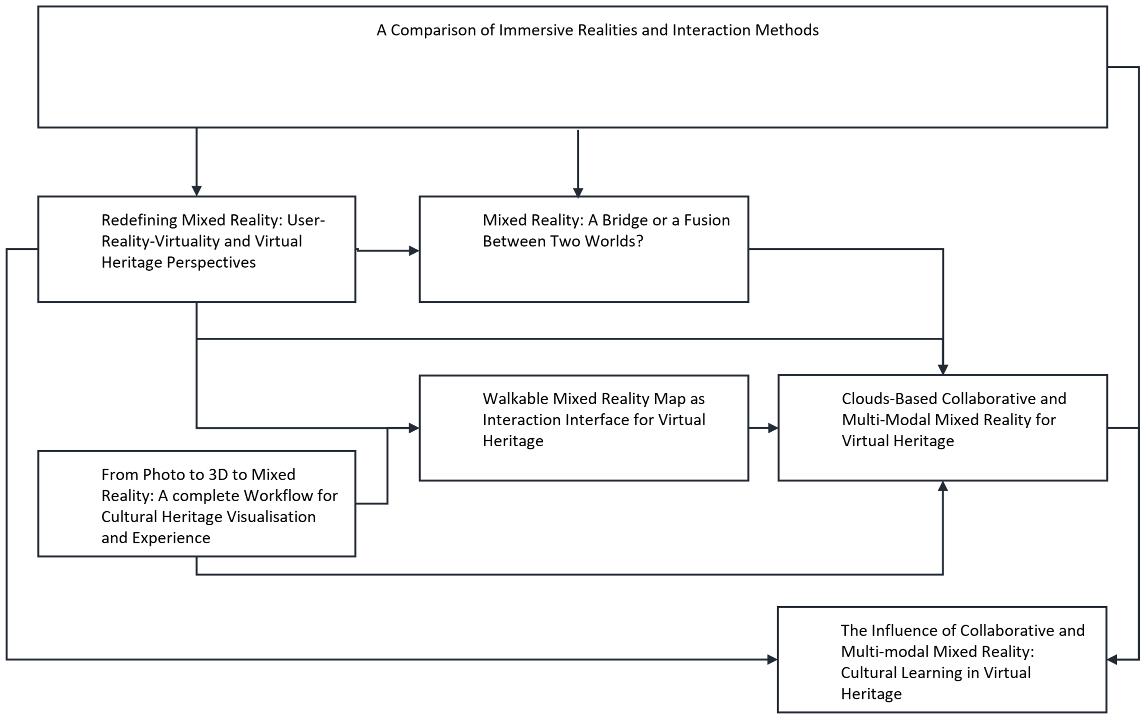

Figure 1.5: Dissertation Structure.

1.11 Abbreviation and Terminology

2D: Two-dimensional

3D: Three-dimensional

AEC: Architecture, Engineering, and Construction

AMC: Audio Media Creation

AR: Augmented Reality

AV: Augmented Virtuality

BIM: Building Information Modelling

CAVE: Cave Automatic Virtual Environment

CC: Cultural Computing

CH: Cultural Heritage

CHP: Cultural Heritage Professionals

CMCM: Cultural and Multimedia Content Manager

CMCS: Cultural Multimedia Content Storage

CMIF: Collaborative and Multi-Modal Interaction Framework

DB: Database

DoF: Degrees of Freedom

FOSS: Free and Open Source Software

GAR: Geospatial Augmented Reality

GIS: Geographic Information System

GLAM: Galleries, Libraries, Arts and Museums

GPS: Global Positioning System

GUI: Graphical User Interface

HCI: Human-Computer-Interaction

HHD: Hand-Held-Devices

HMD: Head-Mounted-Displays

IMU: Inertial Measurement Unit

MAAWA: Maritime Archaeological Association of Western Australia

MR: Mixed Reality

MRTK: Mixed Reality Toolkit

MxR: Mixed Reality

SAR: Spatial Augmented Reality

SfM: Structure from Motion

SLSM: Shared Location and Session Manager

SS: Steamship

URV: User-Reality-Virtuality

VH: Virtual Heritage

VR: Virtual Reality

Chapter 2

A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage

Publication review:

1. Identifies common interaction methods employed in virtual heritage and discusses immersive reality technologies in the context of cultural learning and virtual heritage.

2. Establishes collaboration, engagement, and contextual relationship as experiential factors the enable cultural learning in virtual heritage.

3. Compares various interaction methods and immersive reality technologies against their potential to enable collaboration, engagement, and contextual relationship.

4. Following the comparison, this study identifies hybrid interaction method (collaborative and multi-modal) and mixed reality as suitable combination to enable cultural learning in virtual heritage.

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A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage

Mafkereseb Kassahun Bekele† and Erik Champion†*

UNESCO Chair of Cultural Heritage and Visualisation, School of Media, Creative Arts and Social Inquiry, Curtin University, Bentley, WA, Australia

In recent years, Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR) have become popular immersive reality technologies for cultural knowledge dissemination in Virtual Heritage (VH). These technologies have been utilized for enriching museums with a personalized visiting experience and digital content tailored to the historical and cultural context of the museums and heritage sites. Various interaction methods, such as sensor-based, device-based, tangible, collaborative, multimodal, and hybrid interaction methods, have also been employed by these immersive reality technologies to enable interaction with the virtual environments. However, the utilization of these technologies and interaction methods isn't often supported by a guideline that can assist Cultural Heritage Professionals (CHP) to predetermine their relevance to attain the intended objectives of the VH applications. In this regard, our paper attempts to compare the existing immersive reality technologies and interaction methods against their potential to enhance cultural learning in VH applications. To objectify the comparison, three factors have been borrowed from existing scholarly arguments in the Cultural Heritage (CH) domain. These factors are the technology's or the interaction method's potential and/or demonstrated capability to: (1) establish a contextual relationship between users, virtual content, and cultural context, (2) allow collaboration between users, and (3) enable engagement with the cultural context in the virtual environments and the virtual environment itself. Following the comparison, we have also proposed a specific integration of collaborative and multimodal interaction methods into a Mixed Reality (MxR) scenario that can be applied to VH applications that aim at enhancing cultural learning *in situ*.

Keywords: mixed reality, collaborative interaction, multimodal interaction, virtual heritage, cultural learning

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Jolanda Tromp,
Duy Tan University, Vietnam

Reviewed by:
George Papagiannakis,
Foundation for Research and Technology Hellas, Greece
Spyros Vosinakis,
University of the Aegean, Greece

****Correspondence:***
Mafkereseb Kassahun Bekele
mafkereseb.bekele@postgrad.curtin.edu.au

†These authors have contributed equally to this work

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INTRODUCTION

The benefits of immersive reality technologies and Human-Computer-Interaction (HCI) methods for the preservation, representation and dissemination of cultural heritage have been widely researched in CH (Addison and Gaiani, 2000; Papagiannakis et al., 2008; Adhani and Rambli, 2012; Anthes et al., 2016; Bekele et al., 2018). Although critical technical limitations, such as lack of robust and real-time tracking and lack of intuitive interaction interfaces, hinder users' experience, immersive reality technologies have achieved a fascinating acceptance in various application areas of VH (Carrozzino and Bergamasco, 2010). This trend has resulted in an increasing utilization of immersive reality and HCI methods in the contemporary museums, tourism industry, and the VH domain. The dissemination of these technologies within traditional museums and heritage sites, however, has been challenged by a number of factors, such as its cost of installation, and demand of high-end computers and programming expertise (Carrozzino and Bergamasco, 2010). Furthermore, the technology keeps advancing quite often, meaning cultural institutions, and professional need to acquire the new technologies and the appropriate skills for content development. In the last few years, however, a significant number of affordable immersive reality headsets and hand-held devices equipped with a higher graphical computation, positional tracking sensors, and rendering capability are changing the trend. As a result, immersive reality technologies and HCI methods are being exploited for educational, explorative, and exhibition enhancement purposes (Scott et al., 2018; Zhao et al., 2018). Eventually, such developments can change the position of traditional museums and heritage sites toward accommodating the installation of immersive reality technologies. However, an effective utilization of these technologies needs to be supported by informed practical guidelines. In this regard, this paper will present a comparison of AR, VR, AV, and MxR technologies and HCI methods that are commonly adopted in VH applications. A similar comparison of immersive environments has been attempted by Kateros et al. (2015). However, the authors focused on gamified VR and HCI rather than the full spectrum of the reality-virtuality continuum. Our paper, on the other hand, attempts to compare the whole spectrum and a wider range or interaction methods in order to assist in predetermining their relevance to VH applications. In addition, the paper attempts to identify the best approach in terms of integrating a specific form of immersive reality and interaction method to enable cultural learning in a specific VH scenario.

The remainder of this paper is organized as follows. Section Immersive reality technologies discusses the segments of the reality-virtuality continuum and their enabling technologies. Different categories of interaction methods are discussed as an aspect of immersive reality enabling technologies under this section. Section Comparing Immersive Realities and Interaction Interfaces provides a comparison of immersive realities and interaction interfaces against three factors (contextual relationship, collaboration, and engagement) borrowed from existing scholarly arguments in the CH domain. Following the comparison, the section will also provide suggestions as to which forms of immersive reality and interaction methods can enhance cultural learning in VH applications. Finally, section Conclusion provides a conclusion and summarizes the paper.

IMMERSIVE REALITY TECHNOLOGIES

In the past, immersivity and presence have been associated with or regarded as indicators of a successful VR application due to the technological constraints that made immersivity a unique quality of VR. As a result, the applicability of such aspects hasn't been realized in AR and MxR applications until recently. However, the recent advances in Head-Mounted-Displays (HMDs) enable audio-visual immersivity in all of the segments of the reality-virtuality continuum. For instance, one of the recent HMDs "Microsoft HoloLens," which is built mainly for an AR/MxR experience, can also be used for VR scenarios. Such potentials are changing the trend of the enabling technologies behind immersive reality in terms of establishing a versatile platform where any segment of the continuum can be implemented upon. Hence, it is crucial to discuss immersive reality from two different perspectives: (1) focusing on its forms (categories), and (2) focusing on its enabling technologies.

Forms of Immersive Reality

Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR) are specific segments of the reality-virtuality continuum. In order to avoid a repetitive appearance of "AR/VR/AV/MxR," the term "immersive reality" will serve as a collective term representing these segments. However, when there is an explicit reference to a specific segment, the appropriate term will be used.

Azuma (1997) defined AR as "a system that combines real and virtual content, provides a real-time interactive environment, and registers in 3D." In general, AR aims to enhance our understanding or perception of the physical environment. This could be achieved by adding digital content to our view of the physical environment or by virtually erasing some parts of our view. The adoption of AR into VH began in early 2000s. The ARCHEOGUIDE project is a typical example (Vlahakis et al., 2001). Over the las decade, following the availability of relatively affordable immersive reality devices studies in the VH domain have established AR as a system that enhances users' view and understanding of CH assets (Liarokapis et al., 2005; Kim et al., 2009; Zoellner et al., 2009; Haydar et al., 2011; Damala and Stojanovic, 2012; Casella and Coelho, 2013; Rattanarungrot et al., 2014; D'Auria et al., 2015; Leach et al., 2018).

Virtual Reality (VR), on the other hand, transports users to a highly immersive virtual environment without any or little possibility of directly interacting with their immediate physical surroundings (Carmigniani et al., 2011). VR has the potential to simulate imaginative and existing physical environments along with their processes. The simulations can be tuned to a highest level of multisensorial realism in order to affect users' visual, auditory, tactile, vestibular, and even olfactory and gustatory senses (Zhao, 2009). VH applications have extensively employed VR for virtual reconstruction, simulation, educational, and explorative themes (Gaitatzes et al., 2001; Mourkoussis et al., 2002; Christou et al., 2006; Haydar et al., 2011; Pietroni et al., 2013).

Similar to AR, Augmented Virtuality (AV) also attempts to enhance users' understanding of the environment it is applied to. To this effect, AV augments virtual environments with live scenes of events and elements from the real-world. Due to virtual simulations serving as the base environment in AV, this segment could be misunderstood as a variation of VR. This is problematic since the whole purpose of augmenting virtual environments with live scenes is to enhance our understanding of the underlying virtual environment, which diverts from VR's aim.

Furthermore, VR has no direct implication on our perception of the real world, which to some extent AV achieves since live scenes are streamed from the real world. Interaction and presence in a virtual environment that simulates the physical world in real time might indirectly influence our perception of the physical reality. AV applications are very rare due to the technical challenge of tracking the pose of elements from the real-world and the difficulty of on the fly 3D reconstruction and streaming of scenes from the real-word into the virtual one. However, a recent study by Lindlbauer and Wilson (2018) attempted to perform a live 3D reconstruction of the physical environment where a VR user was physically situated. The authors used eight Kinect cameras for a room-scale coverage to stream scenes from the real word.

Mixed Reality (MxR) blends the real and virtual environments in different forms and proportions. MxR applications are emerging in the VH domain following the recent advances in immersive reality technologies. For instance, Pollalis et al. (2018) presented a MxR application that utilizes Microsoft HoloLens to allow object-based learning through mid-air gestural interaction with virtual representations of museum artifacts. Similar to AV, MxR applications are not common in VH. There are a number of valid reasons as to why this is the case. First, the technological requirements of blending real and virtual elements to the extent that the blend appears as real as the real environment is extremely challenging. Second, MxR has been understood as a variation of AR or a fusion of AR and VR rather than a self-standing form of immersive reality (Piumsomboon et al., 2019). Third, AR and VR have been considered as the default immersive reality technologies in the domain (Haydar et al., 2011; Papagiannakis et al., 2018). As a result, VH has been adopting these technologies following their growing popularity rather than predetermining their relevance or comparing their potential against the intended VH application's requirements, which our paper attempts to achieve.

Enabling Technologies of Immersive Reality

The immersive reality categories discussed above rely on and benefit from display technologies, tracking and registration mechanisms, interaction methods, and virtual environment modeling techniques (Billinghurst et al., 2015; Bekele et al., 2018; Kim et al., 2018). Interested readers can refer to these papers for detailed discussion on the enabling technologies. However, the sections below will briefly discuss these essential aspects of immersive reality. **Figure 1** will also summarize the discussion.

Tracking and Registration

Tracking refers to the process of determining users' viewpoint position and orientation. Immersive reality systems require tracking to superimpose and display virtual information relative to users' or the camera's viewpoint position. In general, there are three categories of tracking techniques commonly used in immersive reality. Those are camera-based, sensor-based, and hybrid tracking methods.

- Camera-based tracking uses a digital camera, vision algorithms, and markers (markers can be in printed forms or infrared emitting devices). Camera-based tracking has two variations. The first one requires markers that need to be attached to a target and the vision algorithm determines the pose of the target that has a marker detected though the camera. The second variation of camera-based tracking relies on markerless and inside-out tracking mechanisms. A typical example is the environmental understanding and tracking cameras in Microsoft HoloLens.
- Sensor-based tracking uses different types of sensing devices, such as electromagnetic, acoustic, and inertial sensors installed at a base station and measurement points. Under this category tracking relies on measuring the intensity of signals and the time taken by the sensors to transmit and receive signals.
- Hybrid tracking is a combination of different tracking devices and techniques, such as GPS, Inertial Measurement Unit (IMU), motion sensors, and eye tracking.

Audio-Visual Presentation Technology

Presentation devices are the core of immersive reality. Based on the type of the virtual content, presentation devices are further classified into visual, auditory, and tactile presentation devices. This paper, however, discusses visual display devices, because most of existing visual display technologies are also capable of audio content presentation. There are five types of displays in this category: Head-Mounted-Display (HMD), Spatial Augmented Reality (SAR), Hand-Held-Devices (HHD), desktop screen and projection, and Cave Automatic Virtual Environment (CAVE).

- HMDs are highly immersive and commonly utilized across all immersive reality categories. Usually, HMDs made for AR and/or MxR are either video or optical see-through, whereas HMDs built for VR and/or AV experiences are blocked headsets since users' direct view to the physical environment is blocked.
- Spatial Augmented Reality (SAR) projects virtual information directly on the real environment through video-projectors. Two or more projectors are used for 3D effects.
- HHDs are portable displays such as smartphones and tablets. This group of displays have become a popular platform for mobile AR. These devices can also support VR if they are combined with additional VR kits such as Google Cardboard and RoboVR.
- Desktop screens and table-top projectors are common display systems for non-immersive VR and AR applications with a limited interactivity. These displays can provide 3D experiences with the addition of stereo glasses.
- The CAVE is a projection-based display technology that allows multiple co-located users to share fully immersive VR experiences. However, it is difficult to adjust the displayed content relative to all users at once, because tracking all users' pose and correcting the content's perspective to the tracked pose at the same time is challenging. Usually, a single user's pose is tracked to continuously correct the VR content's perspective relative to this user and the remaining users' experience is the same as the tracked user.

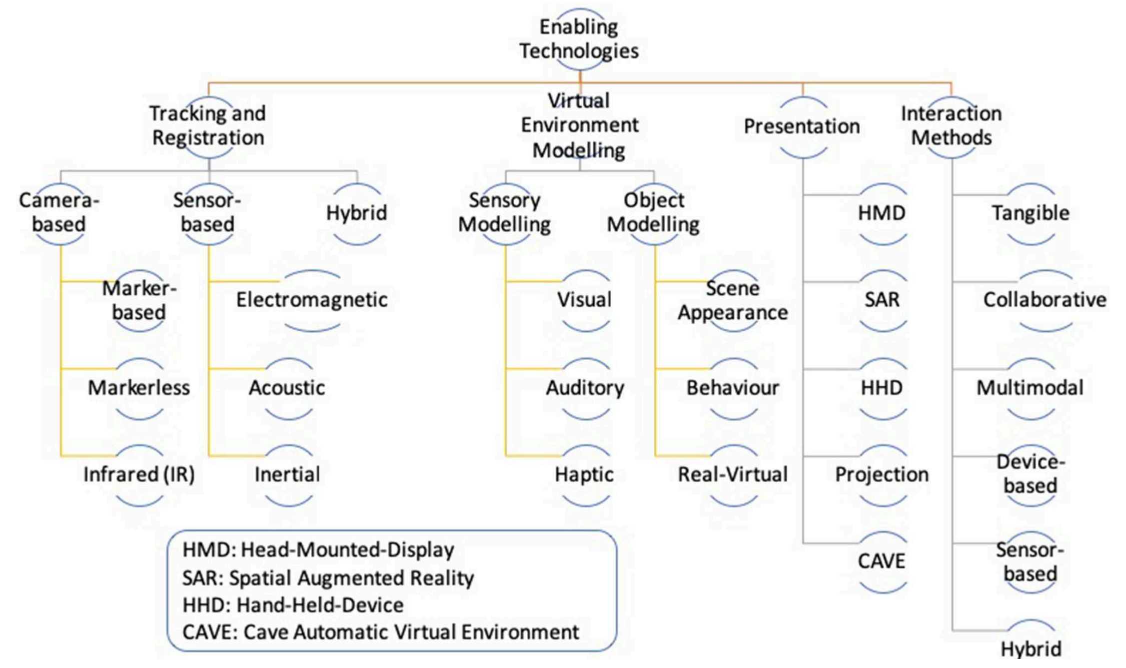

FIGURE 1 | Enabling technologies of immersive reality, summarized from Bekele et al. (2018).

Interaction Methods

Interaction between users and virtual content is a crucial element of any immersive visualization environment. This is even more true for VH applications where cultural leaning is impacted by the interaction with virtual content. The common types of interaction methods are: tangible, collaborative, device-based, sensor-based, multimodal, and hybrid interaction methods.

- Tangible interfaces allow direct manipulation and interaction with virtual information through physical objects.
- Collaborative interfaces often use a combination of complementary interaction methods, sensors, and devices to enable a co-located and/or remote collaboration among users.
- Device-based interfaces use GUIs and conventional devices, such as mouse, gamepad, joystick, and wand to enable interaction and manipulation of virtual content.
- Sensor-based interaction interfaces use sensing devices to perceive users' interaction inputs. The common types of sensors include motion trackers, gaze trackers, and speech recognisers.
- Multimodal interfaces are a fusion of two and more sensors, devices, and interaction techniques that sense and understand humans' natural interaction modalities. This interface group allows gestural, gaze-based, and speech-based interaction with virtual content. Multimodal interfaces are closely related to sensor-based interfaces. However, the former combines multiple modes of interaction.
- Hybrid interfaces integrate a range of complementary interaction interfaces to devise a method that combines different characteristics from the above categories. For instance, a combination of collaborative, and multimodal interfaces.

Virtual Environment Modeling Methods

In general, the commonly used techniques of virtual environment modeling can be categorized into sensory modeling and object modeling methods. From a sensory modeling perspective, the methods are further classified into visual, auditory, and haptic sensorial modeling. From object modeling perspective, on the other hand, the methods are categorized into scene appearance, physics-based behavior, and real-virtual environment modeling (Zhao, 2009). Of these, scene appearance and real-virtual modeling methods are commonly used in VH applications, because the scene appearance modeling focuses on representing the geometric and spatial aspects of objects and the real-virtual modeling focuses on the interfusion of real and virtual scenery. When modeling virtual environments, there are three factors that need to be considered to determine the relevance of a method. Those are, complexity of objects in the real world, intended multimodality of interaction with the virtual environment, and the expected degree of model fidelity (Zhao, 2009). Furthermore, model data acquisition techniques such as photogrammetry and laser scanning are used to generate data for 3D reconstruction and simulation of cultural assets. Hence, an ideal approach to virtual environment modeling would be a combination of modeling methods and 3D data acquisition techniques.

COMPARING IMMERSIVE REALITIES AND INTERACTION INTERFACES

Virtual environments have the potential to serve as a platform that facilitates cultural learning (Ibrahim and Ali, 2018). Similarly, the importance of interaction methods for virtual environments to enable engagement and cultural learning has been emphasized (Tost and Economou, 2009; Champion et al., 2012; Caputo et al., 2016). Furthermore, it has been demonstrated that learning in virtual environments may not be achieved if the interaction method is not easy to operate or if the novelty of the interface overshadows the content (Economou and Pujol, 2007). Hence, balancing interaction, engagement, and content is very crucial for learning. More specifically, cultural learning relies on the contextual connection (relationship) between users and cultural context, and on some form of collaboration between users (Maye et al., 2017; Rahaman, 2018; McGookin et al., 2019; Šašinka et al., 2019).

Enhancing cultural learning in VH applications, therefore, requires the underlaying immersive reality and interaction method to enable a contextual relationship, collaboration, and engagement between users and the virtual environment (Champion, 2010; Jankowski and Hachet, 2013; Caputo et al., 2016; Rahim et al., 2017). This section will compare immersive reality technologies and the commonly used interaction methods against their potential to enable contextual relationship, collaboration, and engagement. The comparison attempts to establish a baseline to predetermine their relevance for disseminating cultural knowledge and enhancing cultural learning in VH applications.

The first factor, relationship, refers to establishing a contextual relationship between users, cultural context, and the immersive reality systems. Existing VH applications that adopt immersive reality technologies for cultural knowledge dissemination focus on users' interaction with the VH applications (Ridel et al., 2014; Schaper et al., 2017; tom Dieck and Jung, 2017; Caggianese et al., 2018). However, in order for VH applications to enhance cultural learning, establishing a contextual relationship between users, their physical surroundings (museums and heritage sites), and the virtual environment (cultural content) is as crucial as enabling intuitive interaction with the virtual environment. Hence, the relationship factor can be further categorized into three: relationship between user and reality (User-Reality relationship), relationship between user and virtuality (User-Virtuality relationship), and relationship between reality and virtuality (Reality-Virtuality relationship). An ideal immersive reality scenario will combine these subfactors into a User-Reality-Virtuality (URV) relationship (Bekele and Champion, 2019).

The second factor, collaboration, denotes the capability of a virtual environment to allow either a co-located or remote collaboration between a minimum of two users. Collaboration can be considered as both an aspect of VH experience and a form of interaction method. In both cases, the collaborative environment/method mimics or it reflects users' or visitors' experience as it would be at physical museums or heritage sites. Enabling collaboration requires more than a collaborative interaction with a virtual simulation/reconstruction of cultural heritage. It also requires the implemented VH application to influence users' experiential aspects as a result of their collective actions.

The third factor, engagement, is related to the ability of the virtual environment to enable engaging experiences as a result of the combination of immersivity and intuitive interaction with the cultural context in the virtual environment. To this end, VH applications rely on interaction methods, immersive headsets, and relevant cultural context. For instance, combining a tangible interaction method with highly immersive virtual environment and a relevant cultural context can be as engaging as a physical visit in museums and heritage sites (Katifori et al., 2019). Hence, VH applications that balance cultural context, interaction, and immersivity can lead to enhanced cultural learning.

In summary, whether cultural learning can be enhanced in VH applications depends on the capability of the different forms of immersive reality technology and interaction methods to enable contextual relationship with users, reality (cultural asset) and virtuality (virtual content), enable collaboration between users, and enable engagement with both the cultural context and virtual environments.

Immersive Realities for Virtual Heritage Applications

In general, immersive reality technologies enable user-centered and personalized presentation of VH and make cultural heritage digitally accessible. The accessibility can be realized in a form of virtual reconstruction, simulation, or virtual museums. Such characteristic is viable, especially when physical access to artifacts is limited. In addition to increasing accessibility, immersive reality technologies can enhance cultural learning and enable visitors to have their own interpretation of cultural assets (Dow et al., 2005; Chrysanthi et al., 2012; Baldissini and Gaiani, 2014; Bustillo et al., 2015; Chang et al., 2015). In line with the potential and demonstrated capability of immersive reality to enhance learning in virtual environments, our paper attempted to compare current immersive reality technologies aiming at making suggestions as to which technologies can benefit VH applications. Hence, a detailed comparison of immersive reality technologies against the three factors (relationship, collaboration, and engagement) is attempted.

The comparison is performed by carefully assessing whether a given immersive reality technology or interaction method can enable the following:

- Engagement: does the technology or method enable engagement? What is the level of engagement supported?
- Co-located collaboration: does the technology or method support co-located collaboration?
- Remote collaboration: does the technology or method support remote collaboration?

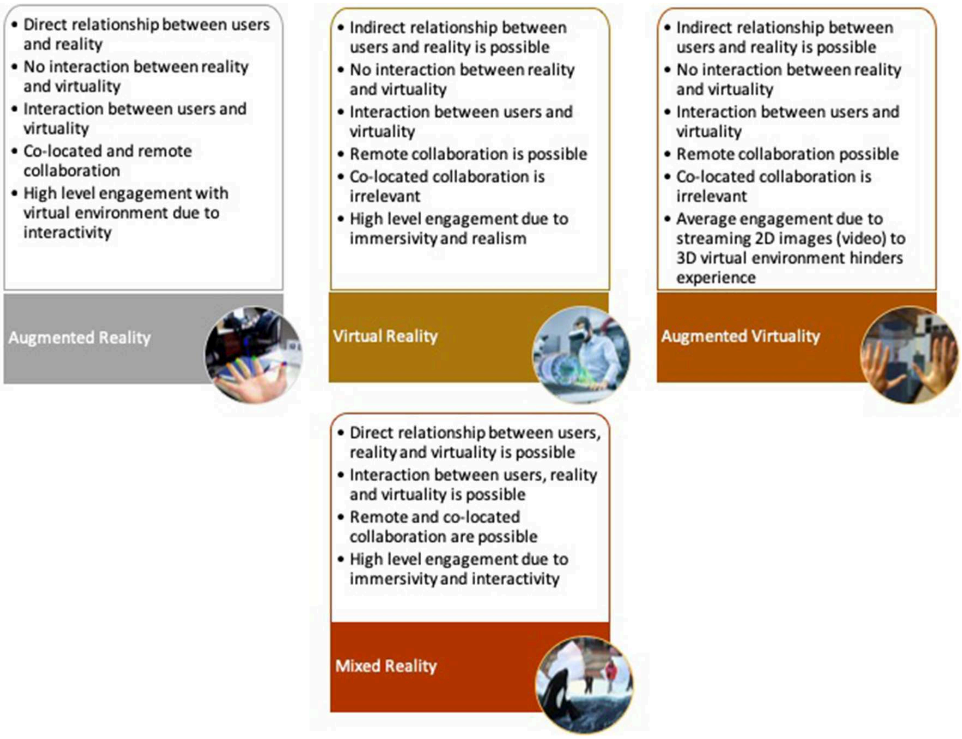

FIGURE 2 | Identified capabilities of immersive reality technologies based on a comparison of their features against the three criteria (relationship, collaboration, and engagement). This figure is a summary of **Table 3**.

- Relationship between users and virtuality: does the technology or method enable interaction and relationship between users and virtuality?
- Relationship between reality and virtuality: does the technology or method enable interaction and relationship between reality and virtuality?
- Relationship between users and reality: does the technology or method enable interaction and relationship between user and reality?

Taking the above questions into consideration, the assessments performed on the current immersive reality technologies and interaction methods are presented in **Tables 3**, **4**, respectively. Furthermore, the assessments are summarized as presented in **Figures 2**, **3**, **Tables 1**, **2** to make the details more presentable.

Mixed Reality (MxR)

Mixed Reality (MxR) is a unique form of immersive reality in a sense that it can provide, if exploited properly, a symbiotic platform where all the three criteria (relationship, collaboration, and engagement) can be balanced to benefit both the real and virtual environments. A contextual relationship between users, reality (cultural elements from the physical environment), and virtual content (3D reconstruction and simulation) can be maintained. This puts users at the center of the experience, affects their senses, and allows users to be part of any change and process in the real-virtual environment. This technology's potential to merge real and virtual elements enable the virtual environment to appear as real as the real. The real-virtual environment helps to enhance our understanding of both worlds, meaning the virtual elements enhance the real world and elements from the real world enhance the virtual one. From a VH perspective, this translates into merging 3D recontractions of lost tangible and intangible heritage elements with their currently remaining portions or natural locations and establishing a relationship between users and the merged environment.

In addition, MxR enables both co-located and remote collaboration. Remote collaboration can be implemented in all forms of immersive reality technology. However, a co-located collaboration is achieved only through AR and MxR, because this kind of collaboration requires users' local collective actions when interacting with the virtual environment. Even if both AR and MxR enable a co-located collaboration, MxR can add immersivity to the experience. Hence, VH applications that require some form of collaboration between users can benefit from a MxR technology.

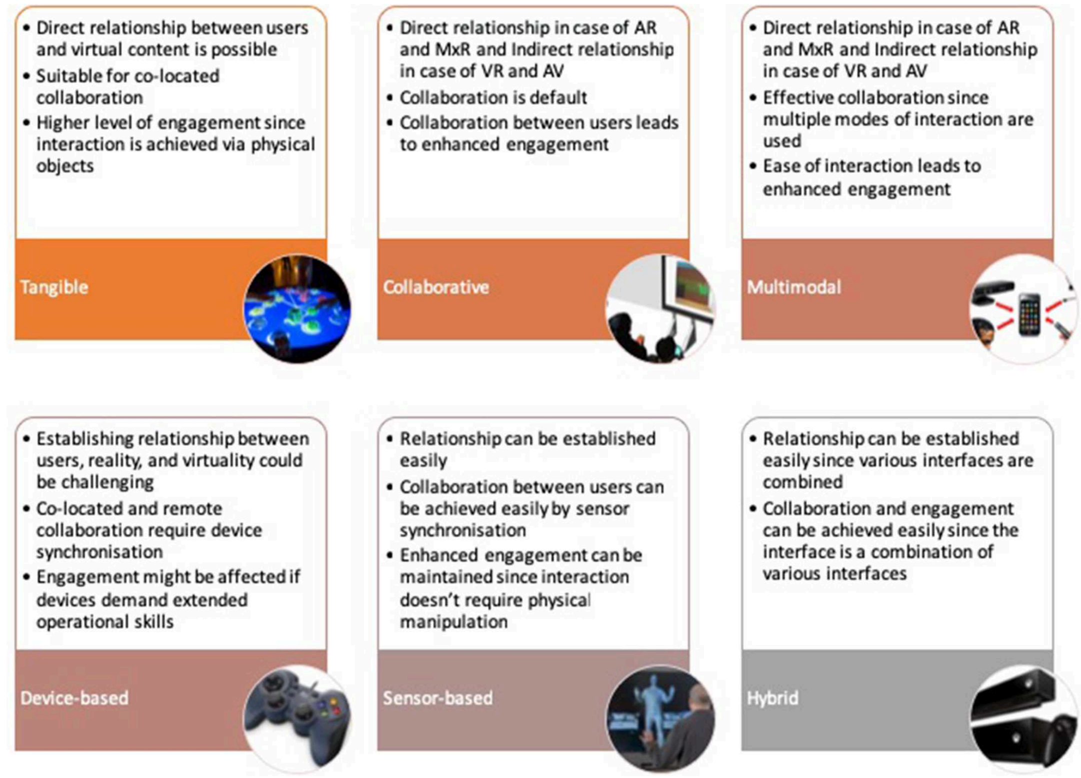

FIGURE 3 | Identified capabilities of current interaction methods based on a comparison of their features against the three criteria (relationship, collaboration, and engagement). This figure is a summary of **Table 4**.

TABLE 1 | Comparison of immersive reality technologies (summary of **Table 3**).

Comparison factors	Immersive reality technologies			
	AR	VR	AV	MxR
Engagement	High	High	Average	High
Co-located collaboration	Yes	No	No	Yes
Remote collaboration	Yes	Yes	Yes	Yes
Relationship (User-Virtuality)	Yes	Yes	Yes	Yes
Relationship (Reality-Virtuality)	No	No	No	Yes
Relationship (User-Reality)	Yes	No	No	Yes

Another feature that puts MxR ahead of AR, VR, and AV is engagement. This experiential aspect can be applied easily in MxR than the other forms of immersive reality, because MxR can combine elements from both the real and virtual worlds. This means virtually reconstructed cultural content can be blended with physical cultural heritage elements at their natural location. All in all, MxR is a viable form of immersive reality to create a VH experience that exhibits the three criteria (relationship, collaboration, and engagement) in order or enhance cultural learning.

It could be argued that AR can enable VH applications to exhibit the same properties as much as MxR does, because both conventionally attempt to enhance our understanding of the physical world by superimposing digital information over our view of the physical environment. However, these two forms are markedly different from experiential and technological perspectives. For instance, AR can't enable a symbiotic relationship between the physical and the virtual environments, it is always the physical environment the avails from the relationship. MxR, on the other hand, enables a symbiotic relationship and interaction between the real and virtual environments. As such, contextual relationship, collaboration, and engagement can be easily implemented in MxR.

Virtual Reality (VR)

Virtual Reality (VR) is highly immersive and transports users to a fully computer-generated world. From a VH perspective, such characteristic enables the reimagination an reconstruction of lost cultures in a highly immersive virtual environment. Interaction in VR is always between users and virtual environments (cultural

TABLE 2 | Comparison of interaction methods (summary of **Table 4**).

Comparison factors	Interaction methods					
	Tangible	**Collaborative**	**Multimodal**	**Device-based**	**Sensor-based**	**Hybrid**
Engagement	High	High	High	Average	High	High
Co-located collaboration	Yes	Yes	Yes	Yes	Yes	Yes
Remote collaboration	No	Yes	Yes	Yes	Yes	Yes
Relationship (User-Virtuality)	Yes	Yes	Yes	Yes	Yes	Yes
Relationship (Reality-Virtuality)	No	Yes	Yes	Yes	Yes	Yes
Relationship (User-Reality)	Yes	Yes	Yes	No	No	Yes

content). There is no direct interaction/relationship between users and the real world, because VR blocks users' view to the physical environment. However, indirect relationship can be established via virtual simulations and representations of the physical world (or some elements from the physical world) in the virtual one.

The fact that users are blocked from the real-world view makes co-located collaboration less relevant to apply in VR. Even if it isn't commonly implemented in VH, remote collaboration can be achieved by representing users as avatars in virtual environments. Of all immersive reality segments, the virtual environments in VR are highly engaging due to their higher level of visual realism, immersivity, and presence. However, all the three criteria can't be balanced in VR—direct relationship between users and the physical environment can't be established, and co-located collaboration is irrelevant in VR since users are blocked from the real world. As such, VR's applicability to VH isn't as versatile as MxR. However, VH applications that don't require merging virtual elements and the physical environment and applications that attempt to reconstruct and simulate cultural heritage elements in a highly immersive virtual environment benefit from VR.

Similar to the close alignment of AR and MxR in terms of their objective, it could also be noticed that VR and AV share a similar goal of transporting users to a computer-generated virtual environment. However, VR and AV shouldn't be perceived as alternates for two main reasons. Firstly, the primary objective of virtual environments in VR is transporting users to a highly immersive and completely computer-generated world in which the user has no chance of establishing a direct relationship and interaction with the physical world. Hence, VR can achieve a higher sense of presence since the user isn't intermittently reminded of the physical environment. AV, on the other hand, streams live scenes from the physical world to the virtual one. This is problematic because it is technically challenging to perform a real-time 3D reconstruction and streaming elements from the real world to AV environments at the same time. Hence, AV applications end up streaming the physical world in 2D and this hinders users' presence and experience. Secondly, even if it is possible to stream 3D scenes from the physical environment, user's interaction and relationship is only with the virtual environment.

Interaction Interfaces for Virtual Heritage Applications

The primary role of conventional interaction methods is to enable users to interact with computer systems. From a VH perspective, however, interaction interfaces play a huge role to create a contextual relationship between users and what the virtual environments represent. Hence, adopting interaction interfaces into VH applications needs predetermining whether a given method meets this expectation. However, it isn't common to come across to VH applications where interaction methods have been selected or customized based on their potential to establish a contextual relationship between users, cultural context and their potential to enable collaboration and engagement. Nevertheless, there are few exemplar cases of VH applications that have effectively used custom-made collaborative, multimodal and hybrid interfaces (Christou et al., 2006; Santos et al., 2010; Huang et al., 2016). In this regard, our paper attempts to compare different categories of interaction methods against the three criteria (relationship, collaboration, and engagement) that VH applications need to exhibit in order to enhance cultural learning. A detailed comparison is presented in **Table 4** and summarized in **Figure 3** and **Table 2**. Following the comparison, collaborative, multimodal, and a hybrid method that combines both were selected for further discussion based on their relevance for enhancing cultural learning in VH applications.

Collaborative Interaction Interface

Collaboration is a default feature in collaborative interaction methods. Such methods require an integration and synchronization of input devices, sensors, and audio-visual presentation technologies, such as gesture sensors, speech recognisers and HMDs (Piumsomboon et al., 2019). The ultimate goal of collaborative interaction is to enable a multiuser interaction with a shared virtual environment, meaning the interaction method has a technical and experiential aspects. For instance, two co-located users interacting with an identical virtual environment aren't necessarily interacting collaboratively unless the users' experience emanates from identical and a shared virtual environment. Hence, collaborative interaction, from an experiential perspective, requires users to interact with a shared, identical, and synchronized virtual environment. In addition, the users' collective or individual act of interaction needs to impact the virtual environment for all users. From a technical point

TABLE 3 | A comparison of different forms of immersive reality technology against relationship, collaboration, and engagement: the comparison assists predetermining the relevance of a given form of immersive reality to enable cultural learning in virtual heritage applications.

Immersive reality	Relationship	Collaboration	Engagement
Augmented Reality (AR)	AR can establish a relationship between users and virtual content (cultural content)	Both remote and co-located collaborations can be implemented in AR	Engagement with the cultural content in virtual environments depends on the interaction interfaces' capability to enable intuitive interaction between users the virtual environment
	Interaction and relationship between users and their physical environment can be maintained since users view to the physical word isn't blocked. However, there is no direct relationship/interaction between the real world and virtual content, except virtual elements are superimposed over the real world		
	Interaction is always between users and virtuality (virtual content), and digital representations or simulations of cultural assets		Tangible and sensor-based interaction interfaces can enhance engagement since they pause relatively lower cognitive load
Virtual Reality (VR)	Interaction is always between users and virtual environments (cultural content)	Remote collaboration can be achieved by representing users as avatars in virtual environments	Virtual environments in VR are engaging due to their higher level of visual realism, immersivity, and presence
	There is no direct interaction/relationship between users and the real world because VR blocks users view to the real environment. However, indirect relationship can be established via virtual simulations and representations of cultural assets in the virtual environment	Collaborative VR isn't common in VH	Sensor-based and device-based interaction interfaces are employed commonly in current VR systems. However, device-based interfaces might hinder the level engagement because users are required to physically manipulate those devices, and this might cause a discontinuation of presence
Augmented Virtuality (AV)	Interaction is always between users and virtual environments (cultural content)	Remote collaboration can be achieved by representing users as avatars in the virtual environment or streaming a live video of users into the virtual environment. However, collaborative AV is extremely rare in any domain	Level of the virtual environment's realism and immersivity can directly determine the extent of engagement in AV
	Indirect relationship can be established between users and elements from the real world since live scenes are streamed from the real world to the virtual one		Usually, scenes streamed from the real world to the virtual environment aren't live 3D reconstructions. Hence, level of engagement could be hindered due to fusion of 2D and 3D images
	The relationship between elements from the real world and the virtual environment benefits the virtual environment		
Mixed Reality (MxR)	A symbiotic relationship can be maintained between the real and virtual environments by blending elements from both worlds	Co-located and remote collaboration can be implemented in MxR	Engagement is higher in MxR in contrast to the other forms of immersive reality since it can combine elements from both the real and virtual worlds. This means virtually reconstructed cultural content can be blended with cultural heritage elements at their natural location
	Unlike other forms of immersive reality, interaction and relationship can be established between users, reality, and virtual environments (cultural content)	MxR is an idea option for VH applications that require face-to-face collaboration at heritage sites and museums	Multimodal interaction interfaces that combine gestural, speech, and movement-based inputs can enhance user's engagement since the cognitive load of operating such interfaces is lower in contrast to other interfaces

of view, collaborative methods need: (1) devices and sensors that can acquire inputs from multiple sources, (2) visual, audio, or some form of cues to inform users when there is any act of interaction being performed by one of the collaborating users, and (3) synchronizing changes in the virtual environment.

Collaborative interaction interfaces can easily establish a contextual relationship between users and cultural content and can add a social dimension to the experience. In this regard, a study by Šašinka et al. (2019) indicates the importance of adding a social dimension to enhance learning in a collaborative and

TABLE 4 | A comparison of different categories of interaction interfaces against relationship, collaboration, and engagement: the comparison assists predetermining the relevance of a given interaction interface to enable cultural learning in virtual heritage applications.

Interaction methods	Relationship	Collaboration	Engagement
Tangible	Tangible interaction interfaces use physical objects to enable interaction with virtual content. This provides suitable setting to establish a direct relationship between users and virtual reconstructions and representations of cultural elements	Co-located collaboration is better achieved with tangible interaction interfaces since users can interact with virtual content via collectively manipulating physical objects. However, this might add extra sophistication to the design and development process since the interface in such cases requires a capability to capture inputs from multiple users	Interacting with virtual content through physical objects enhances users' engagement in virtual environments
Collaborative	Collaborative interaction interfaces enable two or more users' collective actions to enable interaction with virtual environments. This characteristic makes collaborative interfaces a viable approach for establishing a relationship between users, virtuality (cultural content) and the physical environment	Collaborative interfaces are viable mainly for applications that require users to collaborate in order to interact with virtual content disseminated via immersive reality systems	Collaboration between users leads to enhanced engagement in virtual environments as the interface mimics how users interact with cultural heritage collections at heritage sites and museums
Multimodal	Multimodal interfaces enable interaction with virtual content via a combination of different modes of interaction. Gestural, movement, speech, touch, and gaze are the main modes of interaction in this interface Multimodal interfaces resemble how we interact with our physical environment. Hence, this group of interfaces enable users to establish a relationship with cultural context	Collaboration between users is better achieved with multimodal interfaces since such interfaces are versatile and mimic how users would interact with their physical environment	Multimodal interfaces provide enhanced engagement due to the interface's ease of use resemblance to natural interaction
Device-based	Device-based interfaces enable interaction with virtual environments via haptic interfaces, and conventional devices, such as mouse, gamepad, joystick, and wand Enabling a contextual relationship between users, cultural context and virtual environments could be challenging since device-based methods require users to physically manipulate the devices	Most devices in this category of interaction interfaces are designed for individual use. Hence, enabling collaboration across remote or co-located users requires synchronizing the devices, for instance, similar to collaborative video games	In general, device-based interfaces might affect engagement in virtual environments if the devices are demanding in terms the expertise required to operate them. This might interrupt users' presence in the virtual environment
Sensor-based	In general, sensor-based interfaces employ sensing devices to understand different modes of interaction, such as motion tracking and speech recognition. Usually, the interfaces sense users' intention to interact with virtual environments. Hence, these interfaces can effectively maintain an enhanced relationship between users, virtual environments and the cultural content embedded in the environment	Collaboration can be achieved easily by synchronizing multiple sensors. However, current sensor-based interfaces target individual users	Engagement in virtual environments could be higher since the interface doesn't require physical manipulation. This results in a reduced effort to operate the interface and a higher level of engagement
Hybrid	Hybrid interfaces integrate two or more types of interfaces discussed above. As a result, a continuous relationship between users, cultural assets and virtual environments can be maintained by exploiting the strength of each interface	Hybrid interfaces' potential to exploit favorable features from other interfaces put them at a viable position to provide collaborative virtual environments	Hybrid interfaces can achieve a higher level of engagement by integrating collaborative and multimodal interfaces

interactive visualization environment. Collaboration between users, therefore, leads to enhanced engagement in virtual environments as the interaction method mimics how users interact with cultural heritage collections and artifacts in museums and heritage sites.

Multimodal Interaction Interface

Multimodal interaction methods combine multiple modes of interaction, such as speech, gaze, gesture, touch, and movement. To this end, multimodal interfaces use a combination of sensors and devices to perceive humans' natural interaction modalities. Multimodality in immersive reality technologies can be perceived as a multisensorial experience and multimodal interaction. A multisensorial experience refers to users' visual, auditory, kinaesthetic, and tactile senses being affected by the virtual environment and interaction method. A multimodal interaction, on the other hand, explicitly refers to the use of multiple modes of interaction.

FIGURE 4 | A mixed reality scenario showing a virtual ship merged with the physical environment at Fremantle, Western Australia.

FIGURE 5 | A mixed reality scenario showing five co-located users collaboratively interacting with a virtual environment (Image source, Microsoft).

However, a multisensorial experience is implicit in a multimodal interaction method.

Furthermore, multimodal interaction methods resemble how we interact with our physical environment. Hence, from a VH perspective, this group of interfaces enable users to establish a contextual relationship and collaboratively interact with the virtual environment. In addition, these interfaces enable VH applications to provide enhanced engagement with virtual environments and cultural context due to the method's ease of use and resemblance to natural interaction modalities.

Hybrid (Collaborative Multimodal) Mixed Reality for Virtual Heritage

The main objective of collaborative and multimodal interaction methods is enabling collaboration between users and providing intuitive and natural interaction. Here, it is worth it differentiating collaborative interaction method and collaboration in virtual environment. The former explicitly refers to interaction methods/interfaces designed and implemented for collaborative interaction, meaning the interaction methods are designed to target more than one user at a time. Collaboration in virtual environments, on the other hand, refers to the experiential aspect of multiple remote or collocated users' interacting with a given virtual environment. The collaboration itself can be synchronized or asynchronized. The experiential aspect of collaboration in virtual environment is, therefore, implicit in collaborative interaction methods and interfaces. Recent advances in immersive reality technologies, such as the Microsoft HoloLens, are equipped with the necessary technology to enable the implementation of collaborative and multimodal interfaces in VH applications. However, collaborative and multimodal interfaces are still in experimental phases (Funk et al., 2017; Rahim et al., 2017). Furthermore, virtual environments that integrate customized interaction methods into the experience have been attempted (Damala et al., 2016; Signer and Curtin, 2017; Katifori et al., 2019) recently.

Considering similar studies in the past and the comparison presented in **Tables 3**, **4**, this paper proposes a specific integration of collaborative and multimodal interaction methods into MxR. This approach can enhance cultural learning at heritage sites and museums. The enhancement can be realized by exploiting the potential of MxR to merge digital content (3D models, audio, different multimedia) with the physical world (physical artifacts and heritage sites). For instance, **Figure 4** shows a MxR scenario where a virtual ship is blended with the physical world (water environment). Such fusions allow for the dissemination/presentation of virtual reconstructions and simulations of heritage assets at their natural locations. As a result, users will be able to establish a contextual relationship with the real-virtual space.

Furthermore, adding a collaborative and multimodal interaction method to the MxR environment enables a face-to-face collaboration and distribution of interaction tasks among users. Distributing interaction tasks reduces the cognitive load on each members of a group. This leads to enhanced cultural learning since learning in virtual environments is directly impacted by users' effort to interact with the immersive system (Champion, 2006; Wang and Lindeman, 2015). Collaborative MxR reduces the impact since interaction is achieved with less effort from individuals as tasks are distributed among the group members. For instance, **Figure 5** shows a collaborative MxR scenario where five co-located users interact with a shared virtual environment. In addition, the multimodal interaction enables enhanced interactivity and engagement since multiple modes of interaction, such as gaze, movement, speech and gesture, are used to interact with the collaborative MxR environment.

All in all, the proposed approach (Collaborative Multimodal Mixed Reality) can enhance cultural learning by: (1) establishing a contextual relationship between users, the virtual environment and the cultural context, (2) enabling collaboration between users, and (3) increasing the engagement with the virtual environment and the cultural context. To this end, the following technologies can be utilized to enable collaborative and multimodal interaction in MxR environments the primary attempt to enhance cultural learning in VH scenarios.

- Microsoft HoloLens is an HMD primarily designed and built for AR and MxR applications. The device has inbuilt environmental understanding cameras to track users and virtual objects' pose relative to physical objects from their immediate physical environment. In addition, the device has graphics-optimized processing unit.
- Microsoft has developed a development toolkit (Mixed Reality Toolkit) that can be integrated with Unity, which is a popular game engine supporting more than 25 platforms, to develop and deploy MxR application easily to HoloLens.
- Enabling collaboration and multimodality requires synchronization between at least two HMDs (HoloLens). This requires sharing pose, views and virtual objects' location and current state between collaborating users. To this end, cloud services, such as Microsoft Azure Spatial Anchor, Microsoft Azure Cosmos DB and Microsoft Azure Application Service can be used in combination to enable synchronization and sharing virtual objects' pose and current state.

A detailed system architecture, design and implementation of the Hybrid Mixed Reality system proposed above is being performed and the we are currently preparing an article that reports on the first phase of the implementation.

CONCLUSION

In this paper, we have attempted to discuss different categories of immersive reality (AR, VR, AV, and MxR) and their enabling technologies from a VH perspective. We have also attempted to compare these immersive reality categories against their potential to establish a contextual relationship between users, reality, and virtuality and their capability to enable collaboration and engagement in virtual environments. In addition, we have attempted a similar comparison on different interaction methods (tangible, collaborative, multimodal, sensor-based, device-based, hybrid interfaces) in order to identify the best approach from an experiential and technological requirements perspective. Following the comparison, we have identified MxR and VR as potential categories of immersive reality. From the interaction point of view, collaborative and multimodal interaction methods were identified as viable approaches. Finally, we have proposed a specific combination of MxR and a hybrid interaction method comprising collaborative and multimodal features in order to enhance cultural learning at heritage sites and museums. This specific combination can be a practical approach for VH applications to establish a contextual relationship between users and cultural context and implement collaborative experience to add social dimension to the experience. Moreover, it can improve users' engagement with the virtual environment. As an extension to this paper, we plan to present a detailed design and implementation of the proposed approach.

AUTHOR CONTRIBUTIONS

Conceptualization, investigation, resources, and writing original draft by MB. Review and editing by MB and EC. Supervision by EC.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Chapter 3

Redefining Mixed Reality: User-Reality-Virtuality and Virtual Heritage Perspectives

Publication review:

1. Identifies the gap in existing definition of mixed reality from virtual heritage perspective.
2. Identifies contextual relationship, that is one of the three factors to enable cultural learning in virtual heritage, as a fundamental component to redefine mixed reality.
3. Presents a redefinition of mixed reality from a perspective emphasising the contextual relationship between users, reality, and virtuality.

REDEFINING MIXED REALITY: USER-REALITY-VIRTUALITY AND VIRTUAL HERITAGE PERSPECTIVES

MAFKERESEB KASSAHUN BEKELE[1] and ERIK CHAMPION[2]
[1] *UNESCO Cultural Heritage and Visualisation, School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University*
[1] *mafkereseb.bekele@postgrad.curtin.edu.au*
[2] *UNESCO Cultural Heritage and Visualisation, School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University*
[2] *erik.champion@curtin.edu.au*

Abstract. The primary objective of this paper is to present a redefinition of Mixed Reality from a perspective emphasizing the relationship between users, virtuality and reality as a fundamental component. The redefinition is motivated by three primary reasons. Firstly, current literature in which Augmented Reality is the focus appears to approach Augmented Reality as an alternative to Mixed Reality. Secondly, Mixed Reality is often considered to encompass Augmented Reality and Virtual Reality rather than specifying it as a segment along the reality-virtuality continuum. Thirdly, most common definitions of Augmented Reality (AR), Augmented Virtuality (AV), Virtual Reality (VR) and Mixed Reality (MxR) in current literature are based on outdated display technologies, and a relationship between virtuality and reality, neglecting the importance of the users necessarily complicit sense of immersion from the relationship. The focus of existing definitions is thus currently technological, rather than experiential. We resolve this by redefining the continuum and MxR, taking into consideration the experiential symbiotic relationship and interaction between users, reality, and current immersive reality technologies. In addition, the paper will suggest some high-level overview of the redefinition's contextual applicability to the Virtual Heritage (VH) domain.

Keywords. Mixed Reality; Reality-Virtuality Continuum; Virtual Heritage.

1. Introduction

Over the last decade, the segments of the reality-virtuality continuum have witnessed fascinating technological advancements, yet their definitions have remained relatively untouched since they first appeared in the literature back in the 1990s. It is a natural process for definitions and scientific assertions, especially in the technology realm, to continuously align themselves towards current advances and even encode key conceptions that could highlight future developments in

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the realm. Contrary to this natural development, however, the definitions of the reality-virtuality continuum have continued to appear unchanged, still being referred in their original forms. However, their market share keeps growing exponentially and a significant number of research labs dedicate their resources towards advancing immersive reality's applicability and technological bases across diverse domains ranging from medicine and engineering to education and cultural heritage. Hence, given recent developments, redefining the continuum, especially its most contesting segment (MxR), is warranted.

In this paper, therefore, we present a redefinition of the reality-virtuality continuum from a perspective emphasizing the relationship between users, virtuality and reality as a central basis. In addition, a zoomed-in view will be dedicated to MxR and its contextual applicability to Virtual Heritage (VH), a domain emerging in Cultural Heritage (CH) following the advances of immersive reality.

The motivation to redefine MxR is influenced by existing limitations observed in immersive reality and VH studies. This paper aggregates those limitations into three problem spaces: (1) AR and MxR are perceived as alternates, (2), MxR is perceived as a combination of AR and VR, and (3) users are excluded from the defining relationship between reality and virtuality.

Hence, our primary goals here in this paper are: (1) to delineate a boundary between AR and MxR rather than replacing their current definitions with new once, (2) to redefine MxR from a perspective that views the segment as a self-standing form of reality-virtuality instead of an approach that combines AR and VR settings, (3) to augment users' experience into the reality-virtuality relationship in order to redefine the continuum from a perspective that emphasises the relationship between users, reality and virtuality as a central point, and (4) suggest some contextual applicability of the redefined MxR to the VH domain, especially for future VH application that aim to exploit MxR to disseminate virtual reconstructions and simulations of cultural heritage.

To this end, we start by reviewing the current literature in immersive reality technology and exemplar case studies from different application areas to show trends in the uptake of AR, AV, VR and MxR. Moreover, we will compare this trend with the most common definitions of AR (Azuma et al., 2001; Azuma, 1997) and with the reality-virtuality continuum (Milgram & Colquhoun, 1999; Milgram & Kishino, 1994; Milgram et al., 1995) and discuss the interchangeable appearance of AR and MxR in the literature. Secondly, we argue that a relationship between users, reality and virtuality (User-Reality-Virtuality) resolves the issues discussed above and requires redefining MxR. Finally, we outline how the redefinition of MxR can be adopted into VH applications, especially when an application's primary aim is to ameliorate the relationship between users/visitors, cultural heritage sites and their virtual reconstructions or simulations.

2. Existing Definitions of the Reality-Virtuality Continuum

The reality-virtuality continuum (see Figure 1), first introduced by Milgram and Kishino (1994), classified the span between the physical and virtual environments to Augmented Reality (AR), Virtual Reality (VR), Augmented Virtuality (AV), and Mixed Reality (MxR). The continuum and its segments are briefly discussed below as per their appearance in the existing literature.

One of the most widely cited papers, also one of the first definitions of the segment, defines AR as a system that combines real and virtual content, provides a real-time interactive environment, and registers in 3D to enhance our understanding of the physical environment (Azuma, 1997). The sole purpose of AR is to enhance our perception and understanding of the real world by superimposing virtual information on top of our view to the real world.

VR is often referred as a segment of the reality-virtuality continuum that transports users into a computer-generated virtual world, where users are expected to experience a high level of presence in the environment (Carmigniani et al., 2011; Steuer, 1992). Virtual environments detach the users' sense of being here and now in the physical world and create artificial presence in a virtual one instead. To date, the advances in VR have enabled virtual environments to deceive our hearing, visual, and kinaesthetic senses. VR also has the potential to simulate imaginative and existing physical environments along with their processes and environmental parameters to engage and affect all of our senses including touch and smell.

While Augmented Virtuality (AV) augments virtual environments with live scenes from the real-world events, it is commonly understood as a variation of VR. This is problematic since the whole purpose of augmenting virtual environments with live scenes is to enhance our understanding of the underlying virtual environment, which diverts from VR's aim, transporting users to a completely virtual world. Essentially, AV is closely aligned to AR in terms of purpose, because both aim at enhancing the environment they are applied to. VR, on the other hand, has no direct implication on our perception of the real world. However, our interaction and presence in a virtual environment that simulates the real world might indirectly influence our perception of the physical reality.

Milgram and Kishino (1994) defined Mixed Reality (MxR) as "...a particular subclass of VR related technologies that involve the merging of real and virtual worlds." More specifically, they say that MR involves the blending of real and virtual worlds somewhere along the "reality-virtuality continuum" which connects completely real environments to completely virtual ones. However, there are instances where the terms AR and MxR are used interchangeably (Papagiannakis et al., 2018; Raptis et al., 2018). These immersive reality technologies, to some extent, share a common objective, that is enhancing our understanding of the physical environment. However, AR achieves this by overlaying digital content over our view of the physical world and this portion of the continuum is placed closer to reality, whereas MxR achieves a broader goal, enhancing our understanding of the real and virtual worlds, by blending elements from the real and virtual environments. Moreover, contrary to MxR, the academic literature has noted that AR has a limited visual and spatial immersion (Leach et al., 2018). MxR, on the other hand, combines interactivity and immersion from AR and VR, respectively, to bring immersive-interactive experience to our view of the real-virtual word. MxR is thus a broad portion combining different properties of the continuum into a single immersive reality technology. This puts AR in a technically challenging position for consideration as a substitute to MxR.

In conclusion, the most widely known definitions of the reality-virtuality continuum and its segments are derived from a relationship between reality and virtuality and technological advances from their respective eras, most of which are already outdated. In addition, the definitions emphasise on displays rather than on users‘ experience. A redefinition of the continuum from a perspective that doesn’t rely on technology and augments users’ experiential aspect into the reality-virtuality relationship is crucial.

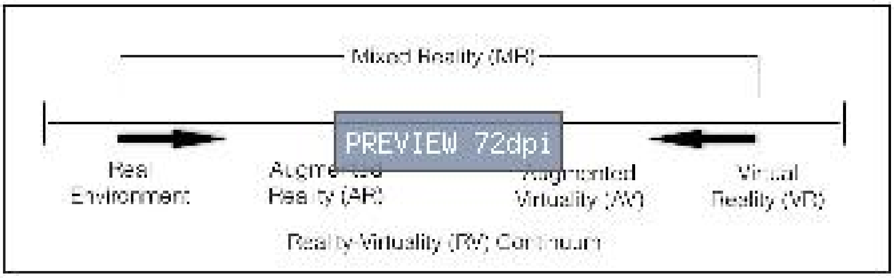

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Figure 1. Reality-Virtuality (RV) Continuum (Milgram & Kishino, 1994). Existing definitions adopt this continuum.

3. Augmented, Virtual and Mixed Reality: Interchangeable, Collective, and Exclusive

This section discusses further the main gaps observed in existing definitions of the reality-virtuality continuum, particularly MxR. We would like to remind readers that the main objective of this paper is redefining the continuum, especially MxR, by redefining existing definitions rather than replacing them with new once.

3.1. AUGMENTED REALITY AND MIXED REALITY ARE PERCEIVED AS ALTERNATES

The term MxR is sometimes used for application that comprise AR characterises (Papagiannakis et al., 2018; Pollalis et al., 2017; Pollalis, Gilvin, et al., 2018). While it is technically challenging to create an immersive reality system or application that delivers AR and MxR experiences at the same time, it has become common to see the terms AR and MxR in the literature, especially since the last two years following the recent display technologies such as Microsoft HoloLens (Scott et al., 2018). However, most of these immersive reality applications demonstrate distinct AR characteristics. Hence, the terms AR and MxR appear in the literature representing identical experiential context. It is technically challenging for immersive systems to exhibit both AR and MxR functionalities because of the technological limitations related to displays. The technical challenge of developing a system that twines AR and MxR features rises mainly from the difficulty in blending dynamic content with dynamic lighting. As such, blending elements from the real and virtual environments to the extent that the fusion appears as believable and immersive as virtual environments in VR is impossible. In addition, MxR application are rare due to lack of robust and real-time tracking and 3D registration, realistic virtual environments, natural interaction interfaces, and presentation devices for vivid experiences (Bekele et al., 2018).

3.2. MIXED REALITY IS PERCEIVED AS A COMBINATION OF AUGMENTED AND VIRTUAL REALITY

Mixed Reality (MxR) is sometimes considered as an umbrella term for systems that comprise both AR and VR characteristics rather than a specific segment of reality along the reality-virtuality continuum (Papagiannakis et al., 2018). These two segments are placed far apart along the continuum and often perceived as the end points of the continuum. AR is positioned close to physical reality whereas VR is the end point of the virtuality side. MxR combines some properties from both segments, interactivity and immersion from AR and VR, respectively. However, it is only VR that is one of the end points of the continuum, AR doesn't qualify as such since it enhances the real world (the other end point of the continuum).

3.3. USERS ARE EXCLUDED FROM THE REALITY-VIRTUALITY RELATIONSHIP

Incorporating users' experience needs to be treated as a fundamental part of any system or application design that somehow involves interaction between users and information. This relationship is a crucial factor that determines the efficiency of interaction interfaces. However, existing definitions of immersive reality and the reality-virtuality continuum haven't incorporated users' experience into the relationship between reality and virtuality that underlies the definitions of the continuum (Azuma, 1997; Milgram & Kishino, 1994). Akin to other Human-Computer-Interaction (HCI) studies in VH (Rahim et al., 2017; Slater & Sanchez-Vives, 2016), where users' experience is highlighted as a crucial aspect of the design and development processes, the interaction and experiential aspects of immersive reality systems need to establish a continuous relationship between users, reality and virtuality. Instead, they try to attract users towards the already established relationship between reality and virtuality. This has made users external observers of the relationship instead of active participants or collaborators in the relationship, influencing its forms and properties.

4. Redefining Mixed Reality: Integrating User's Experience into the Reality-Virtuality Continuum

The novelty of this paper is integrating a users' experiential aspect into the existing reality-virtuality continuum and establish a relationship between users, reality, and virtuality. The redefinitions presented in this paper are inferred from this relationship. The relationship is further discussed in terms of User-Reality-Virtuality Interaction and Relationship aspects in order to clarify the base for the redefinition.

4.1. USER-REALITY-VIRTUALITY INTERACTION AND RELATIONSHIP

Immersive reality technology's role is not just to enable interaction between users and information, it is more a continuous relationship between users, reality and virtuality that puts users at the centre, affects their senses, and allows users to be part of any change and process in the environment. This contradicts the conventional way we interact with virtual information and virtual environments presented via immersive reality systems. Figure 2 below demonstrates the contextual interaction between users, reality and virtuality. This interaction space can be considered as an extension of the original reality-virtuality continuum.

Arguably, MxR is a tread that connects elements form the real and virtual environments. The notions behind connecting elements form the two environments and connecting the two environments themselves differ. From a technological point of view, a complete fusion of the two environments is very challenging. Even if the two environments are blended completely, the fusion makes no sense as it provokes a fight between the two layers to win the user's attention. The logical approach is, therefore, to merge elements from both environments so that the fusion exhibits real-virtual characteristics. This enables the virtual environment to appear as real as the real. The real-virtual environment helps enhancing our understanding of both worlds, meaning the virtual elements enhance the real world and elements from the real world enhance the virtual one.

For instance, imagine a virtual simulation of a captain on a historic ship, our understanding of the significance of either the ship or the captain will be completed when the two are put together in a real-virtual environment. Alternatively, the captain's simulation can be experienced in a VR environment, but the historical significance may not be noticed or communicated as much as in the real-virtual environment, unless of course the virtual environment in the VR simulates both the captain and the ship. Such environments comprise a unique characteristic of MxR since this segment balances inputs from the real and virtual environments. Contrary to this, the other segments of the reality-virtuality continuum incline either to reality or virtuality. Hence, MxR needs to be positioned somewhere in the middle of the continuum.

Adding users' experiential and interactivity perspectives to the real-virtual environments allows to establish a relationship between users, reality and virtuality. This strengthens the redefinition of MxR, especially in terms of delineating a boundary between AR and MxR. This relationship takes into consideration four aspects: (1) the fusion of real and virtual environments or elements, (2) interaction between users and virtuality, (3) interaction between realty and virtuality, (4) immersion in a virtual environment. Figure 2 shows the interaction between users, different forms of immersive reality, and the real world. Figure 3 shows the relationship between users, fusion of real and virtual environments, immersion, and interaction between users, reality and virtuality. Considering a combination of these aspects, the different forms of immersive reality are redefined as follows.

- Virtual Reality (VR) occludes users' view to the real world and users' interaction is limited to the virtual environment. The sensorial effects on users, users influence on the environment, and interaction with the virtual elements are constrained to the affordance of the underlying technology. The fundamental characteristic of VR is that a continuous two-way interaction and relationship could be established between users and virtuality. In addition, the virtual environment in VR is a completely computer-generated one. Hence, there is no direct relationship and interaction between reality and virtuality.

- Augmented Virtuality (AV) is a virtual environment supplemented by elements from the real world. Unlike VR, there is a relationship between reality and virtuality in AV, that is elements from the real word enhance the virtual one. Users primarily interact with the virtual environment but not with the elements from the real world that are augmented into the virtual environment. It is very rare to find AV applications because feeding live scenes from the real environment into a virtual environment is challenging, let alone interacting with and manipulating those elements. If fully exploited with the right enabling technologies, however, AV has the potential to: (1) generate 3D models, environmental parameters and spatial sound on the fly from live scenes and merging them with virtual environments, (2) allow users to interact and establish a relationship with both the virtual environment and the elements being streamed from the real world. In a broader sense, AV is comparable to AR since both try to enhance the primary environment they are based upon.
- Augmented Reality (AR) supplements the real word with virtual elements and enables users to interact with the virtual elements. Even if virtual elements are superimposed around the physical environment, the interaction in AR is always between users and virtual elements. More importantly, the real environment is dominant and benefits from the virtual elements in order to enhance users' perception of the real world.
- Mixed Reality (MxR) blends elements from both the real and virtual environments to create a real-virtual environment that enhances our perception of both environments. This environment enables interaction between users, virtual elements, and the real world, leading to a user-reality-virtuality interaction and relationship space. Unlike AR, where the real environment is dominant, MxR doesn't allow one environment to dominate the other, instead both environments benefit from each other's elements. This is perhaps one of the fundamental factors putting MxR ahead of AR or any form of reality-virtuality, because MxR targets at enhancing our understanding of both the real and virtual environments. One of the reasons why AR is confused with MxR is that they both seem to benefit from virtual elements. However, AR doesn't enhance virtual elements while MxR enables mutual or reciprocal benefits between the real and virtual elements. MxR is, therefore, an integration of elements from virtual and real environments that allows users to interact with the two worlds that benefit from each other's elements in order to enhance users' understanding of the two worlds.

5. Contextual Applicability of Mixed Reality to Virtual Heritage

Virtual Heritage (VH) is an emerging field that applies immersive reality technologies and digital tools to Cultural Heritage (CH) in order to simulate, preserve, and disseminate tangible and intangible cultural assets in a form of diverse multimedia approaches. In general, MxR enables user-centred and personalised presentation of VH and makes cultural heritage digitally accessible in a form of virtual reconstruction or virtual museum/exhibitions. Such characteristics are viable for CH knowledge dissemination, especially when physical access to artefacts is limited.

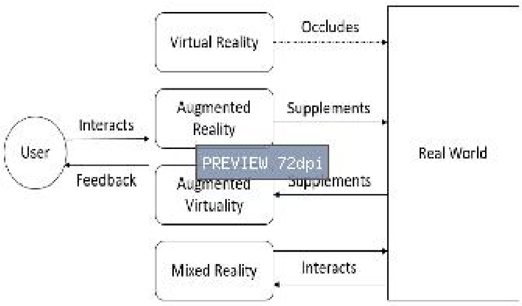

Figure 2. User-Reality-Virtuality (URV) Interaction: Interaction between users, display technologies and the real world.

MxR applications are very rare to find in any domain. Very recently, however, a few applications are emerging in the VH domain following recent advances in immersive reality technologies, such as the Microsoft HoloLens. For instance, Pollalis, Minor, et al. (2018) present an MxR application that utilises Microsoft HoloLens to allow object-based learning through mid-air gestural interaction with virtual representations of museum artefacts. Other examples of HoloLens based applications in the domain include (Baskaran, 2018; Bottino et al., 2017; Pollalis et al., 2017; Scott et al., 2018). Given the redefinition of MxR proposed in this paper, however, these recent studies are more exemplar cases of AR applications that can be tuned to attain the MxR characteristics as per the redefinition.

Following the recent advances and the redefinition presented in this paper, two contextual applications of MxR are proposed for the VH domain. These application areas are, namely, virtual reconstruction and virtual exhibition.

Virtual reconstruction aims at enabling users to visualise and interact with reconstructed historical views of tangible and intangible heritages. Such applications allow merges between historical views from the past with their current appearance. Especially, partially damaged or fully demolished architectural heritages can be virtually reconstructed at their historical location. Additional information beyond the virtual reconstruction itself can also be overlaid along with the virtual elements. MxR plays a great role in the restoration of lost heritages, starting from the reconstruction of statues and extending to reviving cultural practices in their original forms. Leach et al. (2018) present an outdoor AR application that partially achieves a virtual reconstruction of a historical building.

Virtual museums/exhibitions intend to improve visitors' experience at physical museums and heritage sites, typically through personalised virtual tour guidance. In general, such applications simulate or enhance physical museums and heritage sites including their tangible and intangible assets. Such simulations are equipped with potential to enhance cultural presence, thereby bringing a sense of being there and then to visitors. MxR can extend the simulation by including virtual-human characters and cultural agents into the simulated virtual environment. In such cases, the simulation should consider environmental parameters, physical properties, and cultural/historical context of heritage sites. The redefined MxR allows interaction between users, heritages, and virtual simulations. Arguably, such interaction creates a perception of physical movement inside a real-virtual environment. This allows VH application designers to establish a relationship between users and their immediate heritage environment.

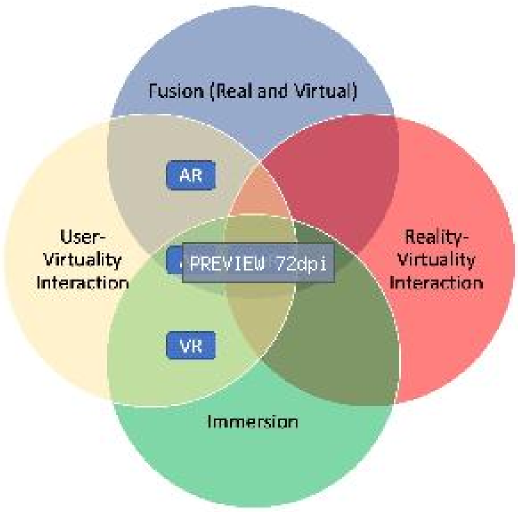

Figure 3. User-Reality-Virtuality (URV) Relationship Space: A relationship between users, fusion of real and virtual environments, immersion, and interaction between users, reality and virtuality. This relationship is the basis for redefining Mixed Reality.

6. Conclusion

In this paper, we have identified major gaps in existing definitions of the reality-virtuality continuum and its segments. Following this, we have presented a redefinition of the continuum from a perspective underlining the important relationship and interaction between users, reality and virtuality. Also, a special focus has been dedicated to MxR when redefining the reality-virtuality continuum. MxR is, therefore, redefined as an integration of elements from virtual and real environments that allows users to interact with the two worlds that benefit from each other's elements in order to enhance users' understanding of the two worlds. Following recent advances and the above redefinition of MxR, two contextual applications are proposed for the VH domain. These application areas are, namely, virtual reconstruction and virtual exhibition.

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Chapter 4

Mixed Reality: A Bridge or a Fusion Between Two Worlds?

Publication review:

1. Based on the redefinition of mixed reality presented in the published work above, this study further explores mixed reality from virtual heritage perspective.
2. Attempts to review the common depictions of mixed reality in exiting body of literature in the context of different application themes in virtual heritage.
3. Establishes a boundary between augmented reality and mixed reality.
4. Conveys the view that mixed reality is a fusion of the real and virtual environment rather than a bridge between these worlds or a combination of properties of augmented and virtual reality.
5. Identifies application themes and limitations of mixed reality in the context of virtual heritage.

CHAPTER 7

Mixed Reality: A Bridge or a Fusion Between Two Worlds?

Mafkereseb Kassahun Bekele
Faculty of Humanities, Curtin University
mafkereseb.bekele@postgrad.curtin.edu.au;
mafkereseb@hotmail.com

Abstract

Virtual heritage (VH) is one of the few domains to adopt immersive reality technologies at early stages, with a significant number of studies employing the technologies for various application themes. More specifically, virtual reality has persisted as a de facto immersive reality technology for virtual reconstruction and virtual museums. In recent years, however, mixed reality (MxR) has attracted attention from the VH community following the introduction of new devices, such as Microsoft HoloLens, to the technological landscape of immersive reality. Two variant perceptions of MxR have been observed in the literature over the past two decades. First, MxR is perceived as an umbrella/collective term for a virtual reality (VR) and augmented reality (AR) environment. Second, it is also presented as a distinctive form of immersive reality that enables merging virtual elements with their real-world counterparts. These

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perceptions influence our choice of immersive reality technology, interaction design, and implementation, and the overall objective of VH applications.

To address these concerns, this chapter attempts to answer two critical questions: (1) what MxR from VH perspective is and (2) whether MxR is just a form of immersive reality that serves as a bridge to connect the real world with a virtual one or a fusion of both that neither the real nor the virtual world would have meaning without a contextual relationship and interaction with each other.

To this end, this chapter will review VH applications and literature from the past few years and identify how MxR is presented. It will also suggest how the VH community can benefit from MxR and discuss limitations in existing technology and identify some areas and direction for future research in the domain.

Introduction

Despite the significant advancements observed in the technological landscape of immersive reality and its expanding applicability across various domains, the perceptions of immersive reality technologies in general or at least their depiction in the VH literature remains influenced by earlier theoretical and technological perspectives – missing current contextual and domain-specific views. For instance, one of the earliest and widely accepted definitions of augmented reality (AR) by Azuma (1997), a segment of the reality-virtuality continuum proposed by Milgram and Kishino (1994), depicts AR as 'a system that combines real and virtual content, provides a real-time interactive environment, and registers in 3D.'

In addition to AR being presented as a system/technology, the characteristics that identify the segment from the rest of the continuum are that it 'combines real and virtual' content and 'provides real-time and 3D interactive environment'. These properties are observed similarly in MxR systems and environments, making AR and MxR identical or interchangeable as they attempt to combine real and virtual content and provide 3D interactive environments. As such, distinguishing AR from MxR relying on such properties is difficult. One of the primary objectives of this chapter is, therefore, to delineate a boundary between AR and MxR, at least from the VH point of view (the assumption is that the boundary between MxR and VR is much clearer as much as it is between AR and VR). To this end, establishing the current depiction of AR and MxR in the literature is required. Furthermore, distinguishing MxR from the rest of the segment requires identifying key factors from the VH perspective.

To date, there are two widely conveyed definitions of MxR in the literature. First, MxR is perceived as a combination of AR and VR. For instance, Elrawi (2017), Makino and Yamamoto (2018), and Plecher et al. (2019) present MxR as a combination of AR and VR environment and/or a collective term representing both AR and VR. This has led to the consideration of AR and VR as the primary platforms for highly immersive and interactive VH applications (Haydar et al. 2011; Papagiannakis et al. 2018). Further to this, the technical complexity and requirements of fusing real and virtual elements, which is a unique property of MxR, to the extent that the blended environment appears as real as the real world has remained extremely challenging. This has to some extent resulted in a lower number of MxR applications and paved a favourable path for AR's and VR's position as the default platforms/technologies.

Second, contrary to the first view, some studies consider MxR as a unique segment of the reality-virtuality continuum that is characteristically and technologically different from both AR and VR. For instance, Jacobs and Loscos (2006), Okura et al. (2015), Bekele and Champion (2019b), and Hammady et al. (2020) present MxR as a technology and virtual environment that amalgamates real and virtual worlds into a single and shared real-virtual spectrum.

Hence, it is evident that a common understanding of MxR is required before an attempt is made to answer the critical question 'Is mixed reality a bridge between two worlds or a fusion of two worlds?'

Contextual Relationship in Augmented and Mixed Reality

The widely accepted definitions of AR and MxR in the literature rely on systems and technological perspectives. Distinguishing MxR from AR and the rest of immersive reality technologies, therefore, requires identifying additional factors from a different perspective rather than the underlying technology and theoretical basis. To this end, an article published by Bekele and Champion (2019b) identifies a contextual relationship between users, the real world, and the virtual environment as a factor that differentiates a specific form of immersive reality from the rest of the segments of the spectrum.

The contextual relationship is realised when the combination/blend of the real and virtual environments enables a three-way interaction between users, reality, and virtuality. Establishing a contextual relationship also relies on how the blended environment resembles and feels as real as the real world. The outcome is an enhanced and engaging real-virtual space that ultimately allows users to establish a contextual relationship with the real-virtual environment. The fusion and the three-way interaction are equally important factors to outline a boundary between AR and MxR. From a VH point of view, communicating or obtaining meaning and cultural significance through immersive reality without a mechanism to establish such a contextual relationship will be a difficult task. Considering fusion and contextual relationship as additional differentiating factors, AR and MxR can be outlined as follows.

Augmented reality is a form of immersive reality that enhances our perception of the real world and allows users to interact with reality and virtuality. Usually, virtual content is superimposed onto our view of the real world. The content could be in any multimedia format ranging from text to 3D models.

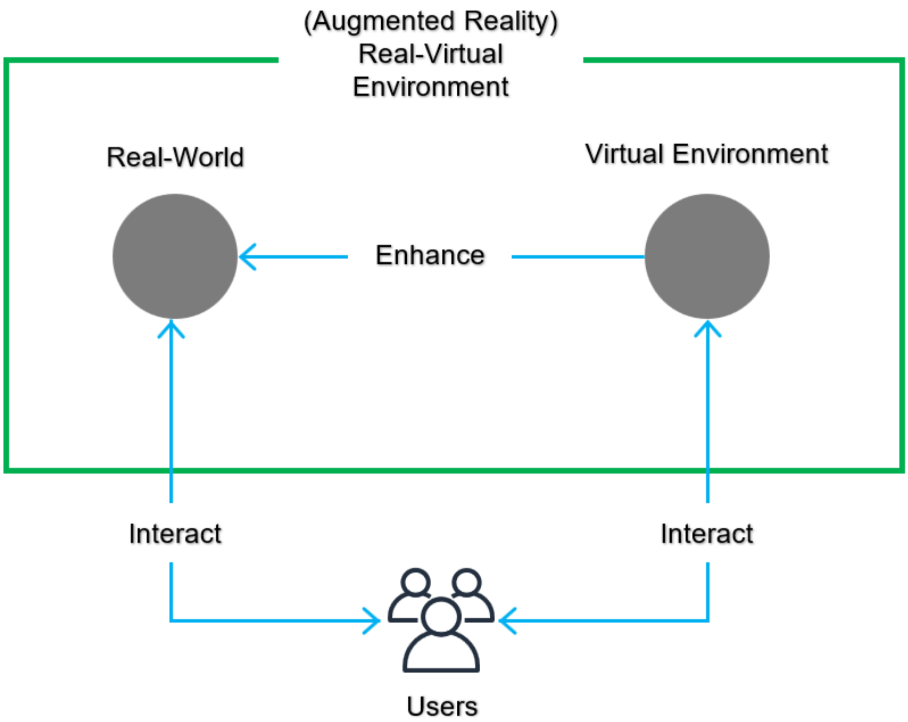

Figure 19: Augmented reality is a form of immersive reality that enhances our perception of the real world and allows users to interact with reality and virtuality (figure produced by the author).

As a result, there is relatively less expectation of the real-virtual environment resembling the real-world.

In addition to this, the resulting real-virtual space in AR does not allow a three-way interaction between users, reality, and virtuality. Users are usually at the centre of the interaction establishing a direct relationship with the real world and the virtual environment. For instance, digital content (text, video, audio, 3D models) of cultural heritage assets can be superimposed over our view of the real world. In some cases, such as virtual reconstruction, digital content can be superimposed on top, or projected next to the same heritage assets in the real world. In this scenario, the virtual environment that is visible to users through AR technology relies on the assets in the real-world to communicate the complete meaning of the multimedia content. The physical assets in the real world would have meaning on their own but users' understanding of the assets' cultural significance would be enhanced with the AR technology. Figure 19 presents AR as immersive reality technology that allows users to interact with a real-virtual environment, enables a contextual relationship between users and the real-virtual environment, and enhances the users' understanding of the real world.

Mixed reality, on the other hand, is a distinctive form of immersive reality that enhances our perception of both the real and virtual environments and

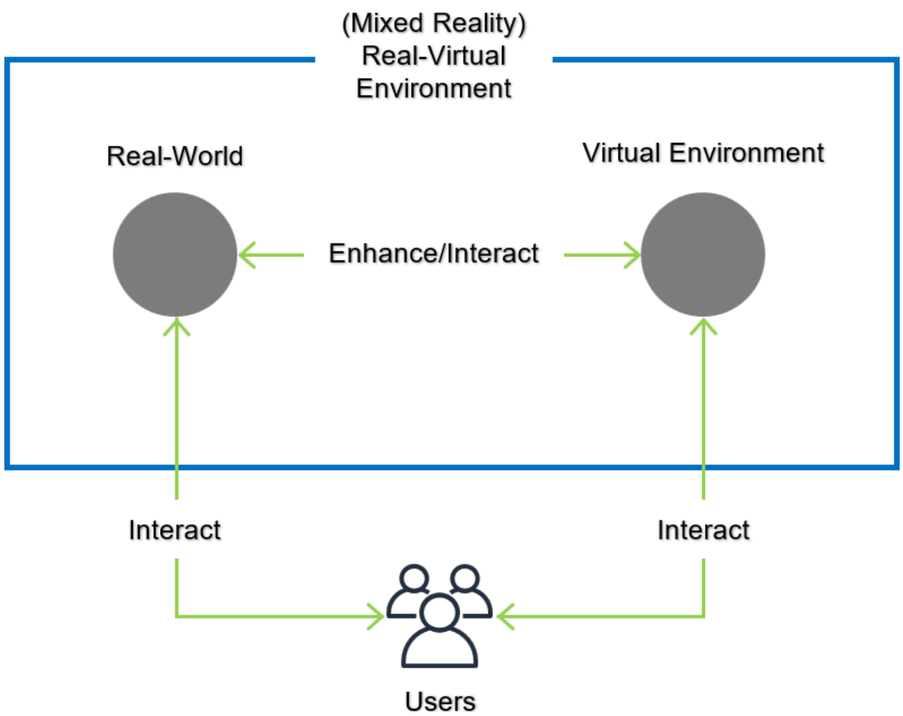

Figure 20: Mixed reality is a form of immersive reality that enhances our perception of both the real and virtual environments and allows interaction between users, reality, and virtuality (figure produced by the author).

allows interaction between users, reality, and virtuality. Figure 20 presents MxR as immersive reality technology that allows users to interact with a real-virtual environment, enables a three-way contextual relationship between users, the real world, and the virtual environment, and enhances users' understanding of both the real world and the virtual environment.

The real-virtual environment (a combination of real and virtual) provides a shared space that elements from both worlds utilise to enhance our understanding of both worlds. In this regard, the difference between AR and MxR is that the virtual environment in AR is limited to enhancing our understanding of the real world. Hence, the relationship between the real and the virtual environment in AR is limited to a one-way direction. The virtual environment in MxR, however, is not limited to enhancing the real world. It also benefits from the real word for delivering enhanced meaning. This arrangement results in a three-way relationship between users, reality, and virtuality.

For instance, consider shipwrecks or physically recreated replica of ships in a museum. Conveying the history and cultural significance of the ships to visitors can be realised via AR (superimposing multimedia content and 3D models) or via MxR (blending virtually simulated 3D animated model of the crew and the physical recreation of ships). Both approaches can enhance visitors' understanding of the ships. However, the MxR approach provides a shared space for both the physical ship and the virtual simulation to communicate the complete picture of the story of the ship. Because, in this scenario, the simulation and the physical heritage asset are highly dependent on each other.

In summary, VH can adopt multiple forms of immersive reality technology to achieve a similar objective (i.e., whether explicit or implicit, VH applications tend to aim at communicating/transmitting the significance and value of heritage assets to visitors/users of the applications). However, considering the available technologies (AR, VR, AV, and MxR), a specific form of immersive reality can deliver the expected outcome more effectively than the rest. This is even more evident when comparing AR and MxR against their potential to enable a three-way contextual relationship between users, reality, and virtuality and blending the real and virtual environments.

As Table 1 shows, MxR exhibits unique aspects especially in terms of establishing a contextual relationship between reality and virtuality and blending the real and virtual environments to the extent the fusion is as real as the real world that results in benefiting both worlds. These unique features of MxR make the technology an ideal choice for VH applications that aim at virtuality recreating or simulating partially or completely lost tangible and intangible heritage assets and blending them with their counterparts that still exist in the real world.

Table 1: Comparison of AR and MxR against their potential to enable a three-way contextual relationship between users, reality, and virtuality and blending the real and virtual environments.

Factor	Augmented Reality	Mixed Reality
Blending the real and virtual environments	Overlays virtual content onto the real world	Virtual content is blended with the real environment resulting in a shared real-virtual environment
Interaction between users and the real world	Users can interact and establish a contextual relationship with the real world	Users can interact and establish a contextual relationship with the real world
Interaction between users and virtual environment	Users can interact and establish a contextual relationship with the virtual environment	Users can interact and establish a contextual relationship with the virtual environment
Interaction between the real world and the virtual environment	There is no interaction between the real world and virtual environment in AR and the sole purpose of the virtual content is enhancing the real world	There is a continuous contextual relationship between the real world and virtual environment in MxR to the extent that specific meaning (e.g., cultural significance in VH) can only be derived from the relationship

Mixed Reality: Bridge versus Fusion

Having the boundary between AR and MxR outlined, this section attempts to determine whether MxR is a bridge that connects the real and virtual world or a fusion of the two worlds that serves as a shared space where contextual relationship, collaboration, and engagement can be realised to a higher degree of realism. To answer this crucial question, we need to establish the aspects and scope of *immersive reality as a bridge* and *immersive reality as a fusion* from the context of VH and the objectives of this chapter.

Immersive reality technology can serve as a bridge between two worlds connecting us to past and/or lost cultures and heritages. In the context of the applicability of immersive reality in VH, the 'two worlds' refer to the existing physical world and a virtually simulated environment that is spatiotemporally distant from the existing physical world. The bridge analogy is, therefore, characterised as a spatiotemporal vehicle that can transport us to a different time and/or a different place. A typical immersive reality technology with such capability is VR. This technology can deliver a platform for highly immersive virtual environments that can simulate multiple dimensions of past traditions, cultures, and heritages. The immersivity of VR is not limited to the spatial and geometrical aspects of the simulated virtual environment. An ideal simulation will consist of multidimensional aspects of the simulated culture/heritage such as temporal, attributive, and environmental parameters. Such simulations can effectively transport us to the past to the extent that we are tricked to believe we are situated there and then.

Alternatively, immersive reality technology can also fuse the real and virtual worlds. From a VH perspective, the fusion of the two worlds is a real-virtual environment that serves as a shared space for the past and the present to coexist (Brondi et al. 2016). Past cultures and civilisations can virtually reoccupy or blend with the existing physical environment. Unlike the bridge analogy, which transports us to a past and distant world, the fusion of two worlds lets us experience the same past and distant world interacting with the existing physical reality that surrounds us. The fusion, therefore, exhibits properties of both the real and virtual environments that ultimately enables a contextual relationship between the two worlds.

All forms of immersive reality technologies except VR can blend real and virtual environments at different levels of interactivity, immersivity, and contextual relationships between components. For instance, a properly designed and implemented augmented virtuality (AV) system can blend the real and virtual environments in real-time. In this case, a live scene from the real world is streamed into the virtual environment rather than cases of AR where the fusion results in virtual content augmenting the real world. With both AV and AR, there is always a dominance of one environment over the other. The third alternative is an MxR technology where the fused real-virtual environment serves as an equally shared space for both realities. However, technological advancement is far from a state that such fusion can be realised to its full extent. Considering existing technologies, however, MxR is a typical form of immersive reality that is best suited for fusing the real and virtual environments.

Relying on how MxR is outlined in the context of VH in this chapter, the environment in MxR is a fusion of two worlds rather than a bridge between two worlds. This is because:

- MxR enables a contextual relationship between users, reality, and virtuality.
- MxR provides a balanced and shared space for elements from both the real and virtual worlds to interact with each other.
- Both the real and virtual worlds can be meaningful by themselves (unlike AR, where the virtual environment relies on the real world to be meaningful).
- Both worlds depend on each other for enhanced meaning.

Mixed Reality and Virtual Heritage

A significant number of studies have demonstrated the role of immersive reality technology in terms of enriching cultural heritage sites and museums with engaging, interactive, and immersive experiences (Hammady et al. 2020). Recent technological advancements have made MxR even more beneficial and accessible to VH applications that tend to target virtual reconstruction in situ. Considering such recent development and trends, the followings have been identified in the literature as viable application themes of VH:

1. Virtual reconstruction. Virtual reconstruction relates to the recreation of fully or partially lost tangible or intangible cultural heritages. MxR is the best choice for VH applications with such themes because the technology can blend the reconstructed virtual environment with physical objects that exist at the historical location of the cultural heritage assets (Montagud et al. 2020).
2. Virtual exploration. VH applications designed for virtual exploration aim at knowledge and insights discovery because of the VH application's capability to afford manipulation and meaningful interaction with the underlying data and real-virtual environment (Okura et al. 2015; Tennent et al. 2020).
3. Virtual exhibition. Virtual exhibitions either replace physical museums and heritage sites with simulations in VR or improve/enhance users' experience at museums and heritage sites by blending virtual content with the real world, for instance, virtual tour guides in MxR (Trunfio & Campana 2020).

4. Virtual educational tools. To some extent, all the above applications serve as tools to educate/inform users regarding the historical and cultural aspects of the content presented in the applications. However, effective dissemination of cultural significance (cultural learning) requires VH applications that primarily focus on the outcome and learning aspects of the virtual content, application design, and implementation of immersive reality. To this end, MxR is a viable choice as the technology enables engagement, interaction, and contextual relationship with the real-virtual environment (key characteristics of VH applications that aim at cultural learning).

Current Issues and Future Directions

Mixed reality technology as it stands has several limitations hindering its wider adoption. The limitations identified in existing studies include rendering performance, lack of robust environmental tracking solutions, and a lack of easy-to-use multimodal interaction interface (Bekele 2019). Considering ongoing research on cloud-based immersive reality and human-computer-interaction (HCI), it is expected that future research will focus on the following areas:

1. *Cloud-based rendering*. Rendering is perhaps one of the key technical issues that MxR applications face across domains. It is even more problematic in VH applications that present sophisticated 3D models with millions of polygons. Even the market-leading MxR device, Microsoft HoloLens, struggles to render 3D models with such a large number of polygons. As a result, decimation is required to reduce the number of polygons, which will then deduce details from the model impacting user experience and the vividness of the rendering. However, Microsoft Azure announced a cloud-based remote rendering service as part of their MxR solutions. The remote rendering service will handle all the graphical computation workloads from the MxR device. Meaning, sophisticated 3D models can be rendered remotely and streamed to the MxR device, which is the Microsoft HoloLens.
2. *Cloud-based tracking*. Sensor and camera-based tracking solutions are commonly adopted in existing VH applications. However, these solutions, particularly in outdoor settings, remain error-prone, impacting user experience. In this respect, new cloud-based services, such as Microsoft Spatial Anchor, provide the possibility of utilising cloud computing to store, share, and retrieve location data of points of interest for MxR applications across multiple platforms and devices. Meaning, VH applications can target multiple devices for user experience while maintaining a shared and centralised pose tracking solution.

3. *Multimodal interaction interface*. An ideal multimodal interaction interface combines multiple modes of interaction allowing users to interact with virtual environments as they would interact with the real world (Bekele & Champion 2019a). This is a key property of MxR experience. Existing technologies rely on gaze, gesture, and speech inputs to enable multimodality in interaction interfaces. For instance, Microsoft HoloLens utilises all three inputs. As research advances in sensor technology, artificial intelligence, and tangible interaction, more advanced multimodal interaction interfaces will likely become a common method of interaction in VH, thereby enabling engaging, interactive virtual environments that users can effectively relate to and interact with through all their senses.

Conclusion

This chapter has presented different perceptions of MxR, especially in the VH domain. It has also outlined a boundary between AR and MxR before attempting to answer the key question raised in the chapter 'Is MxR a bridge between two worlds or a fusion of two worlds?' Immersive reality technology's capability to establish a contextual relationship between users, reality, and virtuality and believability and realism of the real-virtual environment resulting from the fusion of the real and virtual worlds were used as differentiating factors. I have identified application themes and limitations for MxR and VH applications as well as future research areas and directions that I invite you to explore.

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Chapter 5

From Photo to 3D to Mixed Reality: A Complete Workflow for Cultural Heritage Visualisation and Experience

Publication review:

1. Provides, demonstrates, and shows practical implementation of methods to generate 3D models.

2. Provides workflow for deploying 3D models to Microsoft HoloLens device.

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From photo to 3D to mixed reality: A complete workflow for cultural heritage visualisation and experience

Hafizur Rahaman [a,*], Erik Champion [b], Mafkereseb Bekele [c]

[a] Research Fellow, Faculty of Humanities, Curtin University, Australia
[b] UNESCO Professorial Chair in Cultural Heritage & Visualisation, CIC and AAPI, Faculty of Humanities, Curtin University, Australia
[c] Curtin University, Australia

A B S T R A C T

The domain of cultural heritage is on the verge of adopting immersive technologies; not only to enhance user experience and interpretation but also to satisfy the more enthusiastic and tech-savvy visitors and audiences. However, contemporary academic discourse seldom provides any clearly defined and versatile workflows for digitising 3D assets from photographs and deploying them to a scalable 3D mixed reality (MxR) environment; especially considering non-experts with limited budgets. In this paper, a collection of open access and proprietary software and services are identified and combined via a practical workflow which can be used for 3D reconstruction to MxR visualisation of cultural heritage assets. Practical implementations of the methodology has been substantiated through workshops and participants' feedback. This paper aims to be helpful to non-expert but enthusiastic users (and the GLAM sector) to produce image-based 3D models, share them online, and allow audiences to experience 3D content in a MxR environment.

1. Introduction

Digital documentation and preservation of historical and cultural artefacts has increasingly become an international priority in recent years, because of concerns regards the destruction and damage inflicted on internationally recognised heritage assets located in Afghanistan, Syria, Iraq, and most recently, in Brazil. On the other hand, the emergence of cultural computing (CC) (Haydar et al., 2011; Wang, 2009) and advancement in computer technologies have helped to smoothen the procedure and production of 3D documentation, representation and dissemination of cultural heritage data (Barsanti et al., 2014; Portalés et al., 2009). In particular, the rise of affordable techniques (such as image-based photo modelling) and free and open source software (FOSS) is remarkable.

The domain of cultural heritage has also extended its application of immersive technologies; with augmented reality (AR), virtual reality (VR) and mixed reality (MxR) technologies supporting sensory experiences through a combination of real and digital content. As a reflection of the present trends in the digitisation of 3D heritage assets, we can quickly find studies and research on 3D modelling and their application in AR/VR (Bruno et al., 2010; Rua and Alvito, 2011). Ample studies have been published on image-based modelling software analysing their performance (Durand et al., 2011; Grussenmeyer and Al Khalil, 2008; Wang, 2011), accuracy in 3D production (Bolognesi et al., 2014; Deseilligny et al., 2011; Oniga et al., 2017), algorithms (Knapitsch et al., 2017), and scalability (Knapitsch et al., 2017; Nguyen et al., 2012; Santagati et al., 2013). Additionally, we can also find several studies on approaches in application and use of VR/AR in museums and exhibitions; applied from various perspectives such as learning in the classroom (Wu et al., 2013), group use of AR in a public space (Barry et al., 2012), developing virtual exhibitions (Anderson et al., 2010), supporting interactive experiences through 3D reconstructions (Gkion et al., 2011), and providing low-cost solutions for 3D interactive museum exhibitions (Monaghan et al., 2011) etc.

However, it is rare to find a complete production pipeline, or guide for non-experts who are interested in digitising, sharing, and viewing 3D content in a mixed reality (MxR) environment; despite having a restricted budget. To address the above issues, we present a methodology on 3D digitisation to MxR visualisation of cultural heritage assets; based on proprietary and open access software and service. We present two cases to explain the workflow. Photographs are taken from both mobile phone and digital camera. Image-based modelling technique has been used for point cloud generation (with Regard 3D). 3D mesh has been generated and optimised from the obtained point cloud (with Mesh Lab) and later uploaded online for public sharing and visualising in AR/VR (with Sketchfab). Finally, development of interactive visualisation in a MxR

* Corresponding author.
E-mail addresses: hafizur.rahaman@curtin.edu.au (H. Rahaman), erik.champion@curtin.edu.au (E. Champion), mafkereseb.bekele@postgrad.curtin.edu.au (M. Bekele).

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environment (Microsoft HoloLens) has been achieved with a game engine (Unity 3D and MS Visual Studio). The aim of this paper is to help non-expert users to understand the methodology and follow the workflow to produce image-based 3D models, share them online, and experience the digital assets in VR/AR and even in MxR environment such as HoloLens.

2. Proposed methodology and detail workflow

The reality-virtuality continuum presented by Milgram and Kishino (1994) provided a conceptual spectrum of visualisation technologies spanning the real world and virtual world (Fig. 1), and introduced the core concept of Virtual Reality (VR), Augmented Reality (AR), Augmented Virtuality (AV) and Mixed Reality (MxR). AR enhances users' perception and understanding of the real world by superimposing virtual information and object on top of the view of the real world. VR on the other hand, completely detach the viewer from the real world with a computer-generated environment and offers artificial presence to that virtual world (Carmigniani, 2011). Milgram and Kishino (1994) defined MxR as a subclass of VR that merges the real and the virtual worlds. However, there are instances where the terms AR and MxR are used interchangeably (Papagiannakis 2018; Raptis 2018).

In this paper, we present a methodology of producing 3D digital assets from photographs and later deploy it in a MxR environment with interactivity in supporting cultural heritage visualisation and learning. The 3D models are obtained by using image-based photo modelling techniques (photogrammetry), and the MxR environment is developed in HoloLens. We demonstrate a detailed workflow (Fig. 2) starting from photo acquisition to all the way to 3D reconstruction and AR/VR/MxR visualisation. Additionally, we point out best practice and explain how to avoid some common pitfalls.

3. Photogrammetry/image based 3D modelling

Based on the software/service, image based 3D modelling can be done with the support of remote/cloud computing or in local machine. Software or services such as ARC3D and Autodesk Remake use the power of cloud computing to carry out the data processing. In contrast, Regard3D, PhotoScan, Aspect3D, 3DF Zephyr, 3D SOM Pro etc. process the data on local client machines. Scope of this paper doesn't cover the cloud processing method; the workflow will focus only on those software/applications that run on a local PC workstation. Generally these software packages follow six steps to produce 3D reconstructions/3D models, which includes – (1) Image acquisition (or adding photos), (2) Feature detection, matching, triangulation (or align photos), (3) Sparse reconstruction, bundle adjustment (or point cloud generation), (4) Dense correspondence matching (or dense cloud generation), (5) Mesh/surface generation, and (6) Texture generation. A few software packages also offer cloud/mesh editing within a single package.

3.1. Image acquisition

Image-based 3D reconstruction software creates 3D point cloud with camera poses from uncalibrated photographs. The software determines the geometric properties of objects from photographic images. This process, therefore, requires comparing and reference points or matching pixels across a series of photographs. Quality and certain number of photographs are consequently needed to allow the surface to process, match and triangulates visual features and further generating 3D point-cloud. A mobile phone camera (iPhone 6, 8 megapixels) has been used for photo shooting and twenty-two photos are taken for case-1. Alternatively, fifty photographs for case-2 have been captured with a Canon 600D camera. Photos are taken with the right amount of overlap while repositioning the camera for every photo (more information about image acquisition and associated setting can be found in a paper by Lab, 2018).

3.2. Point cloud generation

3.2.1. Selection of the software

Structure from Motion (SfM) is just one of many techniques for 3D reconstruction of objects and artefacts, and most often been recommended (Nikolov and Madsen, 2016). A wide variety of 3D modelling programs are available based on SfM; ranging from simple home-brew systems to high-end professional packages.

A study from Rahaman and Champion (2019) attempted to measure the quality and accuracy of produced point-clouds by four Free and Open Source (FOSS) software with a popular commercial one.

This study shows that FOSS can create a significant good result/point cloud compared to a commercial product (Fig. 3), and it recommends Regard3D. As visualisation of cultural heritage is the primary objective of this study, acquisition of a visually appealing 3D model generated from a low-cost solution, therefore, has been given priority. Herein Regard3D has been used for creating a 3D point-cloud from the datasets (i.e. a set of photographs).

3.2.2. Point cloud generation

Regard3D is a free and open source structure-from-motion program that supports multiple platforms (Windows, OS X, and Linux). A simple and straightforward graphic user interface (GUI) presents the details of whatever results it produced highlighted in the left tree view. Experimenting with settings is thereby much easier since the user only has to click on a result to see a list of the arguments used to generate it, as well as the running time of that selected step. Similar to other software, the user needs to set a project path first and input a name to start a project (Fig. 3).

Photographs are required to be set (step 1) and matches computed (step 2). Next up is camera registration. In other words the process of determining each camera's position and orientation in the scene (step 3), can be achieved by selecting the match results and click Triangulation. Based on this simple sparse point cloud, users can "densify" the triangulation result (step 4). From the tree view, it is possible to highlight the result of the last step and choose 'Create dense point cloud' (Fig. 4). The dense could (*.ply, *.pcd) can be exported at this stage. Users can also generate a mesh by clicking Create Surface (step 5). If the user has used the CMVS/PMVS in the previous stage, then 'Poisson reconstruction' becomes the only option to create the surface. Colourisation method can be selected either as coloured vertices or texture. At this stage, the user can export the generated surface as *.obj file or directly export to MeshLab as *.mtl file format (step 6).

3.2.3. Result/outcome

The computation details and output of the three cases are presented in Table 2.

Nearby vegetation, trees and other buildings/structures often

Fig. 1. The reality-virtuality continuum presented by Milgram and Kishino (1994).

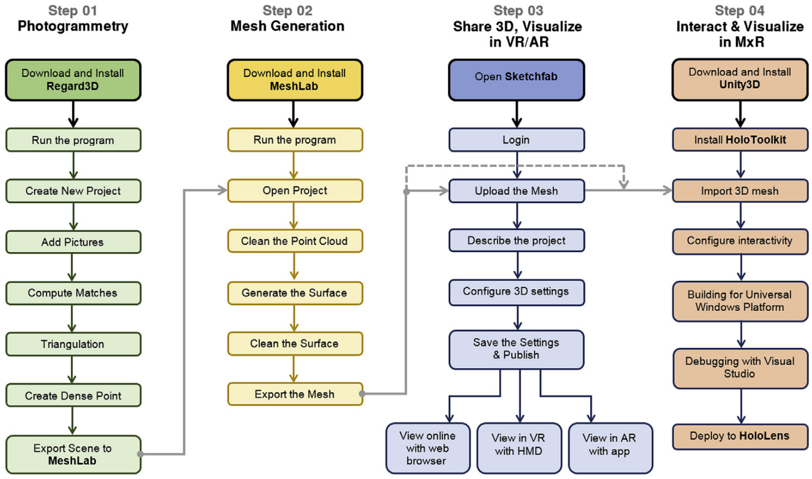


Fig. 2. The overall workflow of 3D modelling to mixed reality visualisation.

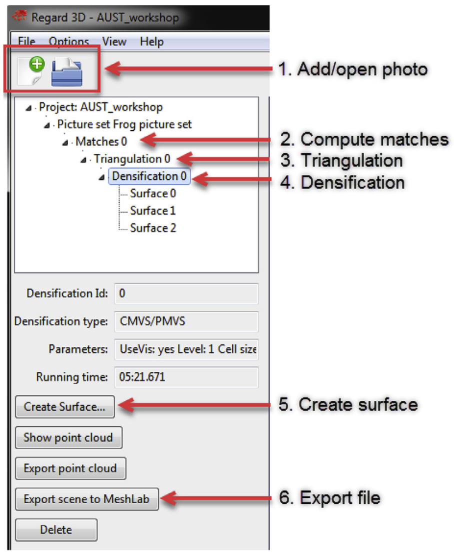


Fig. 3. Workflow offered by Regard3D GUI.

obstruct views for taking photographs of a heritage building. Making a 3D model of a whole building/architecture based on image based photo modelling technique therefore is often challenging. Only isolated buildings and structures are suitable for the application of this image-based 3D modelling technique. Additionally, a larger file takes more time in computation, we avoided larger file sizes in this study. The 3D model of the 'Frog' sculpture was smaller and easier for testing the workability of the methodology and for conducting the workshop.

4. Mesh generation and editing

A mesh is a discrete representation of a geometric model in terms of its geometry, typology and associated attributes (Comes et al., 2014). We used MeshLab (http://meshlab.net), a free and open source software to develop mesh by the generated point-cloud from Regard3D (Fig. 4). After importing the point-cloud in the workspace, it requires cleaning (noise, outliers and irrelevant points). MeshLab provides various tools for selection and removal of points/vertexes.

MeshLab also offers various tools for developing surface reconstruction (or mesh generation) such as Ball Pivoting (Bernardini et al., 1999), VCG (Curless and Levoy, 1996) (ISTI Visual computer Lab), and Screened Poisson Surface Reconstruction (Kazhdan and Hoppe, 2013). We used the Poisson algorithm to generate the mesh (Fig. 5). Additional clearing of the surface may be required at this stage if the process creates unintended surfaces. The acquired mesh can be exported or 'mesh simplification' and 'cap hole' steps can be applied to enhance the 3D model. Mesh simplification reduces the number of polygons while keeping the shape as close as the original. As the number of polygons is reduced, the processing time decrees accordingly. 'Cap holes' on the other hand is self-explanatory; it closes the holes where the previous mesh generation fails to provide/-create any surface/polygon.

Texturing is the operation that offers visual skin/membrane coverage of the 3D models, so that the virtual objects resemble the original. MeshLab can export a wide range of file formats, which supports textures (e.g. *.x3d, *.obj) and vertex/points colour (*.ply). Although most commonly. obj,.vrml, .3dxml and. dae are used for AR applications (Comes et al., 2014), we have exported the mesh as 'Stanford Polygon File Format (*.ply)' for further use.

5. Sharing and visualising the 3D models in AR/VR

5.1. Storing the 3D model

At the time of writing this article, we could not find a clear and foolproof way to preserve/store 3D assets. There are remarkable commercial, public, and hobbyist 3D repositories, ranging from local institutions to international ones; such as CARARE, Europeana, Smithsonian, TurboSquid, Sketchfab etc. It is also clear that despite recent EU and North American moves to create archives and digital heritage infrastructure; 3D models are still not fully accessible to general public (Champion, 2018). Most of the institutional repositories only allow downloading contents with restricted file format. In some cases, only *.pdf files with embedded 3D (such as in CARARE) are allowed. Additionally, it is often difficult to find models from specialised cultural heritage institutional repositories, as they are typically not connected with external sites or portals. On the other hand, commercial repositories often lack data provenance and metadata. However, commercial repositories can provide consistent formats and protocols, and 3D models are relatively easier to find and access. But most of these portals (both

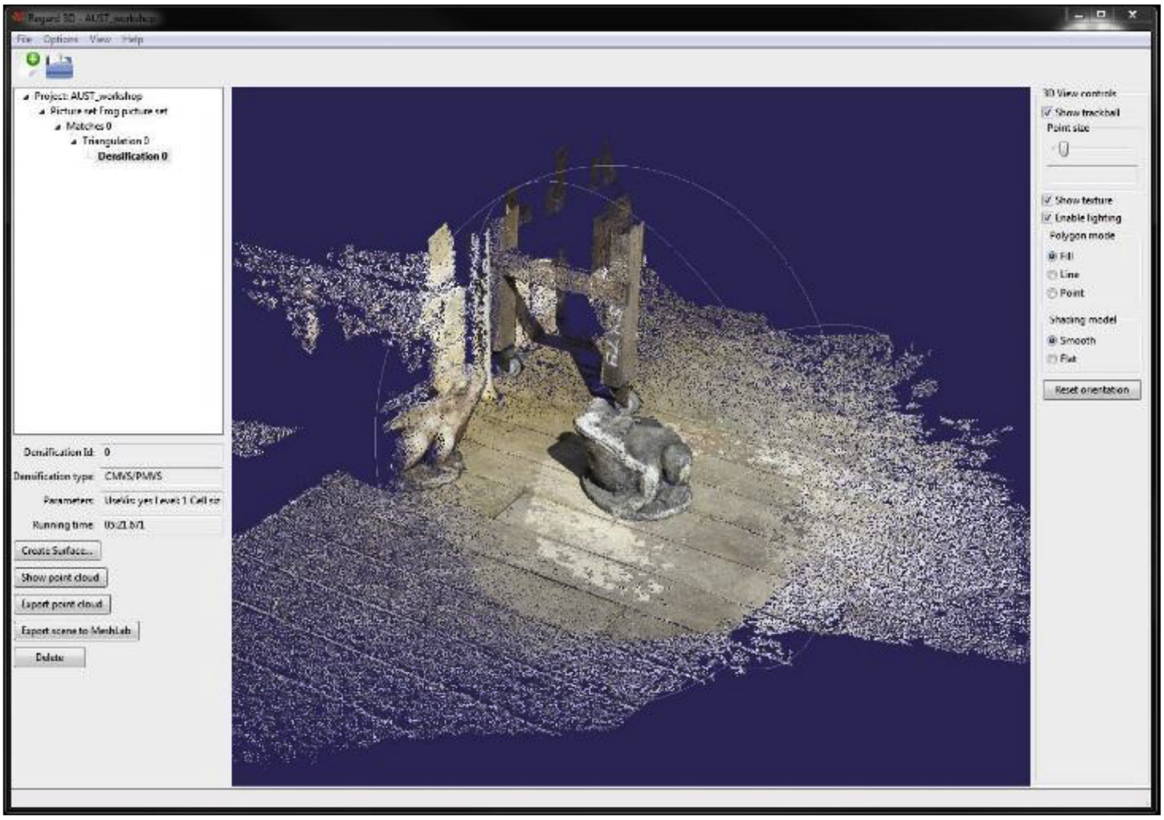


Fig. 4. Dense point cloud created by Regard3D.

commercial and non-commercial) rarely provide other related information and resource links for further study or use.

It is relatively apparent that (at the time of writing this paper), Sketchfab is a commercial platform with flexible and versatile hosting that can support the general public, small institutes and non-profit organisations to host, minor edit, share, trade and showcase their 3D models. These models can later be shared online and viewed in AR/VR with the supplied application. The other commercial repositories such as Turbo Squid, ShareCG, MyMiniFactory and Blendswap are mostly for the trading of 3D models and are not intended for preservation. Additionally, they charge fees on trading and may not interested in archiving (as their archiving policy is not clear).

5.2. Selection of the visualisation (AR/VR) platform

There are number of software frameworks at present to support AR/VR especially suited for cultural heritage. The first criterion is the choice of a single package or solution that supports non-expert users with a limited or restricted budget. Additionally, it is difficult to find a compelling platform or tools that accept a wide variety of file formats, supports cross-platform deployment and visualisation.

There are certain points of overlap between AR and VR since some existing development platforms are suitable for both experiences. A study from Bekele et al. (2018) on most commonly used current AR/VR frameworks has featured their strengths and weaknesses in various settings. However, this study is limited to exploring the tools and not the whole pipeline. Comes et al. (2014) studied 3D AR, AndAR and VaD AR, however, this study focused on simplification of the 3D models rather than evaluating any AR/VR platform. The study from Krevelen et al. (2010) presents the technicalities, development history and characteristics of a wide range or AR technologies.

Portales et al. (2009) have explored various AR platforms and later adopted BazAR (a vision based open source library) to deploy their 3D content. However, to use BazAR user needs to have vision based relative technical knowledge of programming. The workflow adopted by Taboada (2011) for visualising 3D point cloud data in VR only, used OGRE 3D engine (game engine). Studies from Amin et al. (2015) and Guidazzoli et al. (2017) have showcased feature list comparison of various software development kit (SDK) for AR visualisation. Recently, AR toolkits based on visual-inertial odometry tracking have been gaining attention. In particular, the Google ARCore and Apple ARkit look promising. However, it is often difficult for a non-technical person to overcome the steep learning curve in order to use their offered SDKs.

Although X3D and three. js models can run without hindrance in HTML formatted web pages, the issue of choosing 3D file formats best suited for archiving or displaying is still a big challenge in the digital heritage domain. 3DHOP (Potenziani et al., 2015) and Sketchfab are prominent among the relatively few popular services that provide storing, viewing and exhibiting of 3D models online. The open source and free 3DHOP is, however, restricted to *.NXS and *.PLY file format only. Sketchfab, on the other hand, supports more than 50 formats and the free 'basic access' also allows 3D models with a maximum of 50 MB for uploading files (at the time of writing this paper). A comprehensive study on 3D web applications by Guidazzoli et al. (2017) also reveals that Sketchfab competes very well against others for its documentation, ease of learning, GUI, reliability and overall graphics quality. We have

Table 1
Benchmarking of FOSS with PhotoScan (adopted from Rahaman and Champion, 2019).

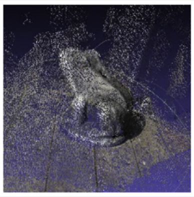
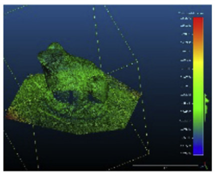
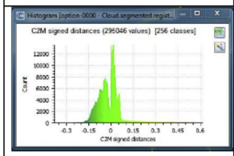
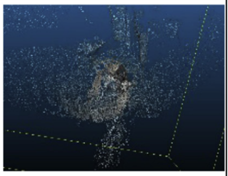
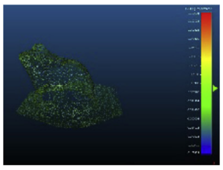
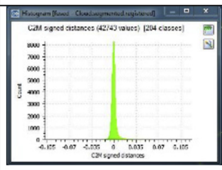
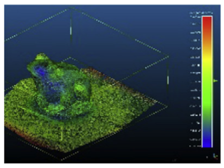
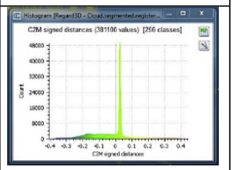
	PhotoScan	Visual SfM	PPT GUI	COLMAP	Regard3D
Pointcloud					
CloudCompare result	N/A (used as ground truth data)	 	 Failed to compare because of noisy cloud	 	 

Table 2
Point cloud generation with Regard 3D.

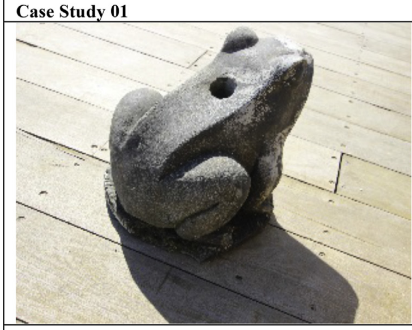
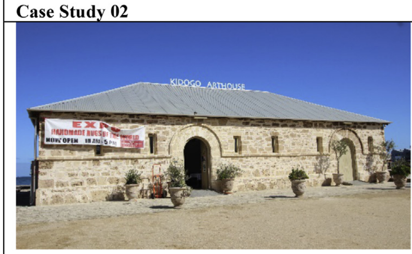
Original object	Generated 3d/point-cloud	Process time
Case Study 01		
		Number of photos: 22 Image matching: 2m12.649s Triangulation: 34.892s Densification: CMVS/PMVS – 4m27.982s Surface generation: 1m 2.725s Total time: 8.5min
Case Study 02		
		Number of photos: 50 Image matching: 27m41.151s Triangulation: 2m 50.710s Densification: CMVS/PMVS – 20m38.443s Surface generation: 1m 4.381s Total time: 52m 21s

Table 3
Selected 3D repositories with common features.

Name	Supported file format	Fees	Accessibility	Data size	3D model display
Public/institutional repositories					
Smithsonian (http://3d.si.edu)	STL, OBJ, Single ASCII point cloud	Free	With few exceptions, SIx3D offers access to the data sets	Download limit is not known	3D
Three D Scans (http://threedscans.com/info)	OBJ, STL	Free	No copyright restrictions	Unlimited	2D, 3D, animated gif
CyArk (http://www.cyark.org)	LiDAR, point cloud, photogrammetric imagery	Free, require online application	Licensed under a Creative Commons Attribution-Non-commercial 4.0 International License	Varies, prior permission required	2D, 3D
Europeana http://www.europeana.eu/portal/en	Jpeg, GIF, PNG, PDF, Plain ASCII, MP3, MPEG, AVI, FBX, mtl, OBJ	Free	Most databases are not accessible anymore	Not known	2D, 3D
EPOCH (http://epoch-net.org/site)	Pdf	Free	Not known	Unlimited	2D
CARARE (http://pro.carare.eu)	PDF, 3D PDF	Free	Not known	Unlimited	3D inside PDF
NASA 3D Resources (https://nasa3d.arc.nasa.gov/)	.stl, .3ds	Free	Non-Commercial Use only	Unlimited	2D
Commercial repositories					
Sketchfab (https://sketchfab.com)	50 popular file formats	Basic & Education access are Free	Varies between paid and free model	Limit based on membership, Unlimited download	2D, 3D, AR, VR
MyMiniFactory (https://www.myminifactory.com)	54 popular file formats	Free/paid option to download and print		Unlimited uploads	2D
Blendswap (https://www.blendswap.com)	37 popular file formats	Free	Varying Creative Commons	Free 200 MB download/m, Upload limit 90 MB	2D
3D Warehouse (https://3dwarehouse.sketchup.com)	.skp	Free	General Model License Agreement	50 MB (max) upload	2D, 3D
TurboSquid (https://www.turbosquid.com)	16 popular file formats	Free and paid	Model Licenses: Various	No restriction	2D, 3D

adopted Sketchfab in the workflow for online sharing and visualisation of the above mentioned 3D models.

5.3. *AR/VR visualisation with sketchfab*

Sketchfab supports 50 extensions (dated 30 October 2017), including compressed archives such as ZIP, RAR and 7z. The GUI offered by Sketchfab for the user dashboard is simple and easy to use. First, the user is required to create a user account in order to upload the 3D content. Generating an account is also possible by signing up with Facebook, Google and Twitter while bypassing the default online form. Sketchfab generally compresses the file first and then starts uploading to the server. We have used the *.ply file saved previously from MeshLab (see Fig. 6).

The system asks for user input/information regarding the model name, description, categories and keywords as metadata. Next, it starts regenerating and take the user to the '3D Setting' mode. Sketchfab's GUI for 3D Settings offers various settings to adjust/control the model (Fig. 7). After getting the desired output the user can press the 'Save Settings' and 'Publish' button to finalise the process.

The universal 3D VR viewer supported by Sketchfab works on most operating systems (Windows, Mac, Linux, iOS and Android) without any required plugin. A user can embed 3D or VR models on any website, forum, or even in Facebook to share their content online. Peers can browse in 3D or VR without leaving the user's own website. The 3D models can also be viewed in VR using various HMD such as Vive, Rift, Gear VR, or Cardboard navigation modes. Most interestingly, via the Sketchfab app installed in a compatible mobile device, one can also view the 3D in AR (Fig. 8).

6. Developing interactivity and visualise in a MxR environment

Mixed Reality (MxR) blends the real-world with the virtual world. It combines interactivity and immersion and offers immersive-interactive experience to view the real-virtual world (Papagiannakis et al., 2018). MxR, therefore, aims to unite different properties of the Milgram and Kishino's (1994) continuum into a single immersive reality experience. Magic Leap, Meta 2, HoloLens are but a few of the many current popular standalone head mounted displays (HMD) that offer a MxR experience. There are some other alternatives (cheaper solutions) in the market such as Holoboard and Mira, which use a smartphone for processing the data and visualisation. However, they are still in their development stage and comparison with the more established group is out of the scope of this present study.

Microsoft HoloLens is an optical see-through Head-Mounted- Display (HMD) developed mainly for AR/MxR experiences. The device can use sensual, and natural interface commands through gaze, gesture, and voice. Gaze commands, such as head-tracking, allows the user to bring application focus to whatever the user is perceiving. Various gestures such as bloom, air tap and pinch are supported for multiple interactions with the virtual object or interface. Any virtual object or button can be selected using an air tap method, similar to clicking an imaginary computer mouse. The tap and pinch can also be used for a drag simulation to move a virtual object. Users can access the shell/interface through a "bloom" gesture. Similar to pressing a Windows key on a Windows keyboard or tablet. Voice commands can also be used to activate actions (source: https://www.microsoft.com/en-us/hololens/hardware, access date 04 April 2019).

A large number of domains are utilising HoloLens for diverse application areas. Even if the utilisation of HoloLens isn't markedly observed in the Cultural Heritage (CH) domain, the last two years have witnessed few Virtual Heritage (VH) applications that were developed using HoloLens. These exemplary HoloLens based applications include Baskaran (2018), Bottino et al. (2017), Pollalis et al. (2017), Pollalis et al. (2018a, b), Scott et al. (2018). However, these articles focus on the experiential aspect of MxR in VH rather than the technical and procedural details that could be of a huge benefit to domain's professionals in terms of developing similar experiences as presented in the articles. In this regard, our paper discusses the major steps required to deploy 3D models into

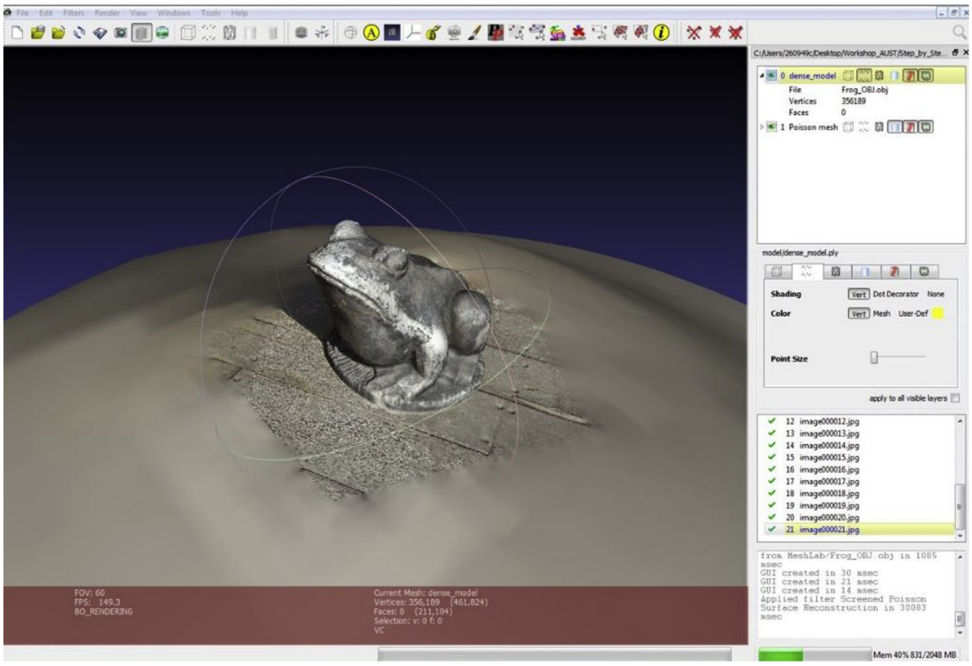


Fig. 5. New surface (Poisson mesh) applied to the point cloud.

HoloLens for a mixed reality experience. The discussion below has been organised for non-expert users of the technology.

6.1. Setting the environment with unity 3D and importing 3D model

As briefly discussed at the introductory section, 'Unity 3D' (or Unity) is a popular cross-platform game engine widely used to develop games. Due to the game engine's popularity, most AR/VR headsets use Unity as a development platform. Similarly, HoloLens uses Unity to develop the intended AR/MxR experiences.

The first step to transferring 3D models to the HoloLens is configuring the Unity development environment. There are two ways to achieve this. The first option is to use the Unity standard configuration procedures.

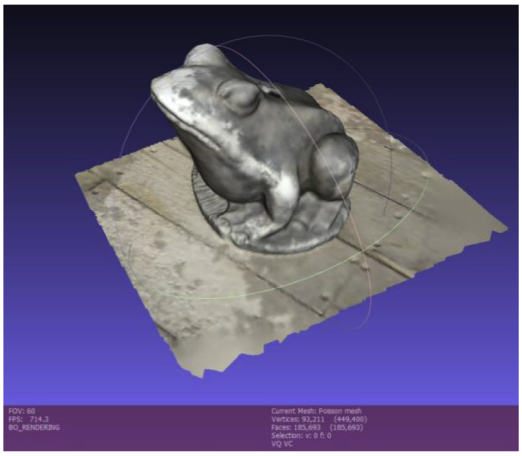


Fig. 6. 3D model after manual cleaning.

The second option is to use the Mixed Reality Toolkit, which is a Unity package consisting of a collection of custom tools developed by Microsoft HoloLens team to facilitate the development and deployment of AR/MxR experiences to the device (HoloLens). This article uses the Mixed Reality Toolkit (Fig. 9).

The Mixed Reality Toolkit was downloaded from a Microsoft HoloLens GitHub repository and imported into a Unity project as an asset package. After importing the Toolkit, configuring the project environment was performed at two levels. The first level of configuration involves applying changes to the "Project Settings" using the "Apply Mixed Reality Project Settings" option from the Mixed Reality Toolkit menu bar (Fig. 9, step 2). This setting configures Unity at a project level. It needs to make sure that, the 'Settings for Universal Windows Platform' is selected, and the 'Virtual Reality Supported' box from XR settings list is checked (Fig. 9, step 3 & 4). This configuration includes scripting backend, rendering quality, and player settings. All configurations have been applied to the present 'scene created' in this specific Unity project.

The second level of configuration applies changes to a specific scene created 'under a project'. This has been achieved using the "Apply Mixed Reality Scene Settings" option from the Mixed Reality Toolkit menu bar (Fig. 9, step 2). For the scene level configuration, we used the toolkit to set the camera position, add the custom HoloLens camera, and configure background colour and rendering settings. After the proper configurations were applied to the "Project Settings" and "Scene Settings", the 3D model generated in section 4 was imported into the Unity project using the platform's asset importing option. Finally, gestural interactivity was implemented on the 3D model to allow users to interact with and manipulate the model via the default gestures recognised by the HoloLens. The Mixed Reality Toolkit has a number of scripts and tools for adding interaction mechanisms to the MxR experience. We have used the toolkit to add gestural and gaze-based interaction mechanisms.

6.2. Building with Universal Windows Platform (UWP)

Unity can build projects for a number of platforms. In this paper,

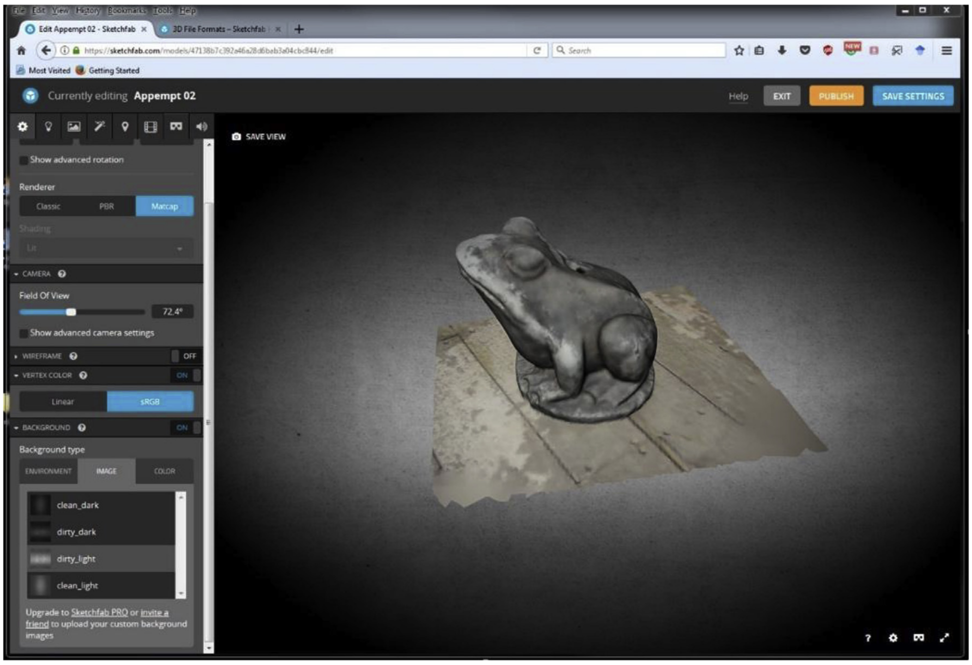


Fig. 7. GUI for 3D settings offered by Sketchfab.

Fig. 8. View the 3D in AR with Sketchfab app.

however, the project was built for the Universal Windows Platform (UWP). UWP is an open source API developed by Microsoft and first introduced in Windows 10 (source: https://visualstudio.microsoft.com/vs/features/universal-windows-platform, dated: 1st March 2019). The purpose of this platform is to help develop universal apps that run on Windows 10, Windows 10 Mobile, Xbox One and HoloLens without the need to write codes for each target device. Hence, a single build can be deployed to multiple target devices. The steps followed before building the project for UWP were: adding a scene to the 'Built Settings', enabling C# debugging; and specifying HoloLens as a target device.

Fig. 10 shows how to configure the built environment and the steps of building the project for UW. First, it requires the user to select the 'Build Settings' from the File menu (Fig. 10, step 2 & 3) and click 'Add Open Scenes' and select the scenes opted for deployment (be sure that the scenes are listed in the 'Scenes In Build' box). A user needs to make sure the 'Universal Windows Platform' is selected as Platform and then select the HoloLens as 'Target Device' (step 4). Check the 'Unity C# Projects' box to enable C# debugging, and finally, click 'Build' (step 5 & 6). At this stage, all the files (including *.sln) required for project deployment to the HoloLens will be created and stored at a location specified by the user.

6.3. Debugging with microsoft Visual Studio and deploying to HoloLens

At this stage, the *.sln file from the "Building with UWP" step discussed above is imported into Microsoft Visual Studio for debugging and deploying to HoloLens. Fig. 11 shows the output of the deployment

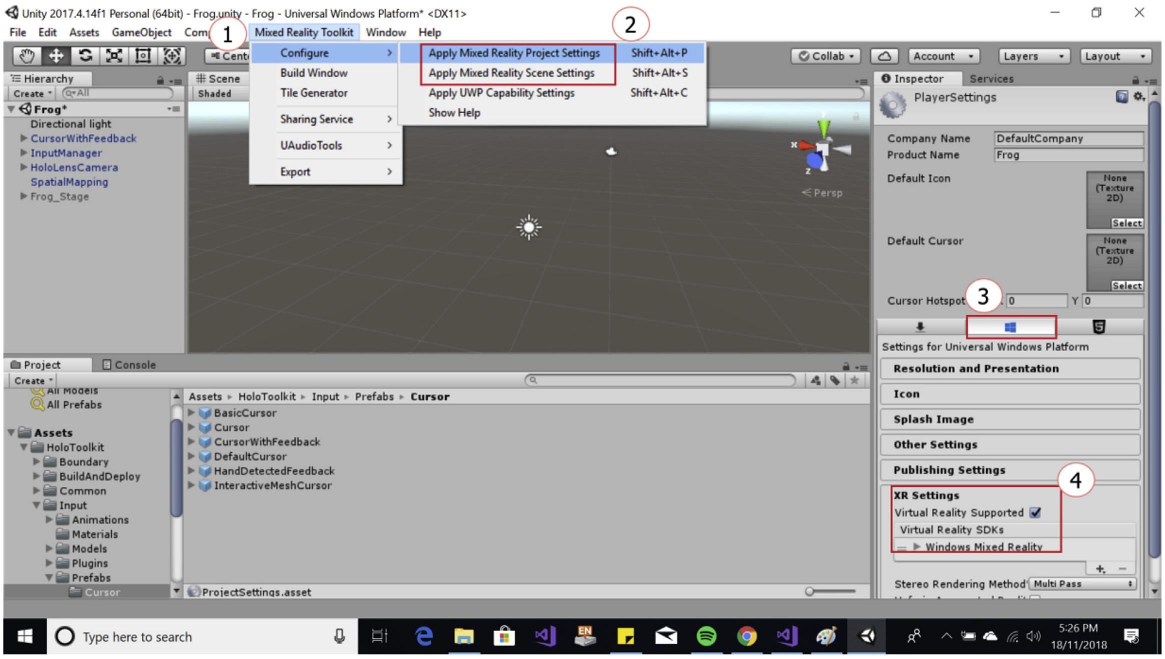


Fig. 9. Configuring Unity project and scene settings to ensure compatibility with HoloLens.

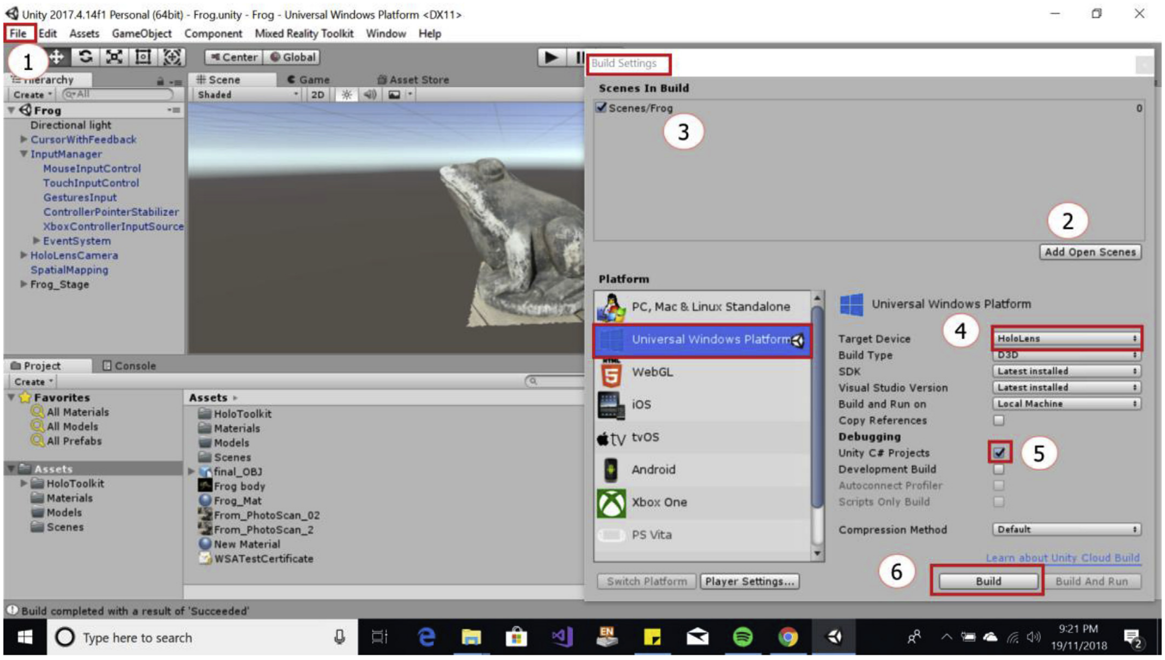


Fig. 10. Building the project for Universal Windows Platform.

process. Deployment can commence by connecting the HoloLens via WiFi or using a USB cable and launching the deployment process from the Debug menu.

The HoloLens must be connected to the computer via USB and the *.sln file created during the build process is opened. To start the process, a user needs to select 'Start Without Debugging' from the 'Debug'' pull-down menu (Fig. 11, step 1). The system will show the output details of the deployment process (Fig. 11, step 2). The user must make sure that

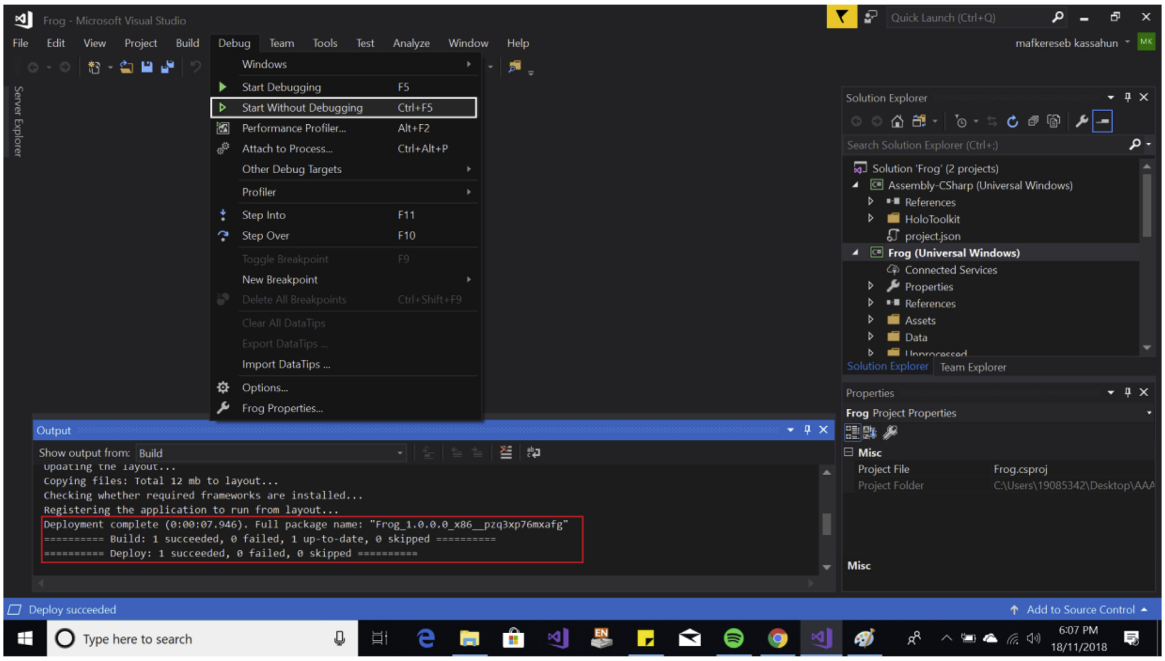


Fig. 11. Debugging and deploying the solution to HoloLens using Visual Studio.

the 'Deploy' count is 1 and 'failed' count is zero. If the deployment is successful, the HoloLens will launch the deployed application by itself.

6.4. *Mixed reality experience in the HoloLens*

Usually, MxR experiences are developed to be used by a single user unless the experience is developed for collaborative use. After the application has been released into the HoloLens, a user can also connect the device to a bigger screen using WiFi for streaming the experience with others. It is difficult to imagine what the HoloLens user is experiencing unless the experience is shared. As a workaround to this issue, HoloLens allows the capturing and streaming of the users' view to another screen, as long as both devices are connected to the same WiFi network. In our case, we used this Mixed Reality Capture capability to stream the HoloLens user's experience (shown in Fig. 12). There are a few seconds lag between the actual experience and the streaming of content to the other person's screen.

7. Demonstration and user feedback

To validate the methodology a workshop was conducted at the Curtin library makerspace, Curtin University, Australia, on 23 November 2018. Fourteen participants attended the workshop, ranging from novice to expert computer users with an age range of 18–60 years. During the workshop, the data sets were supplied to the participants, and they were asked to follow the steps from the instructors. Most of the participants managed to produce the 3D model and reach the final level of deploying the content to the HoloLens. Due to the limited number of HoloLens (one

Fig. 12. A user interacting with a 3D model via HoloLens.

set) and permitted time of the workshop (2 h), only one 3D asset was deployed and interactions were set with simple gestures. The environment with the embedded 3D assets was then shared with the participants to visualise and interact with them. The participants experienced the MxR environment and provided feedback in an informal post-experience discussion. This discussion, however, gives us some remarkable points to ponder for the future:

- Partial workflow (i.e. 3D modelling, editing and AR/VR visualisation with the FOSS) is supported by cross platforms. However, deployment of 3D assets to HoloLens (for MxR) requires Windows 10 operating systems, which prohibited the Mac operating system users from immediate participation or for following the workflow.
- The workflow was found to be workable and easy to follow. The learning of the gesture control to interact the 3D models in a MxR environment based on HoloLens requires time and practise for first-time users. However, they managed to learn the gestures within a short period.
- The workshop duration was limited to 2 h, which evoked complaints from the participants, and we were advised to host an extended session.

8. Conclusion

In this paper, we present a complete workflow for experiencing a 3D model in a MxR environment captured from real-world objects by using proprietary and open access software and service. The workflow starts with digitising 3D artefacts based on image-based photo modelling (photogrammetry), converting a 3D point cloud to a 3D mesh, saving and sharing the 3D model to an online repository, viewing the 3D model in VR/AR, and finally deploying the 3D content to a MxR environment (MS HoloLens) and interacting with the virtual content.

The workflow was demonstrated to fourteen participants in a workshop session, and the users' feedback was collected. User feedback validates the workflow as easy to learn, workable and effective; with a few minor issues. We therefore believe this paper will help non-expert users, as well as small museums, heritage institutes, interested communities and local groups who are interested in digitising their 3D collections, sharing them online and visualising the 3D contents in an AR/VR/MxR environment; especially if their budget is limited and they do not have extensive experience in photogrammetry, modelling, or programming.

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Chapter 6

Walkable Mixed Reality Map as Interaction Interface for Virtual Heritage

Publication review:

1. Proposes and implements a novel approach to use immersive maps as interaction interfaces in a mixed reality environment applied to specific virtual heritage setting.

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Walkable Mixed Reality Map as interaction interface for Virtual Heritage

Mafkereseb Kassahun Bekele

School of Media, Creative Arts, and Social Inquiry, Curtin University, Perth, WA, 6102, Australia

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ABSTRACT

Studies in the Virtual Heritage (VH) domain have led to underlining the significance of a contextual relationship between users, immersive reality technologies and interactive and engaging cultural context as essential aspects towards enabling cultural learning in VH applications. Interaction methods, therefore, play a great role in terms of enabling interactive and engaging experience under various VH settings. This paper proposes a novel approach to use maps as interaction interfaces in a Mixed Reality (MxR) environment that could be applied to specific VH settings with a predefined cultural and historical context. The primary focus of the proposed interaction method named 'Walkable MxR Map' is to use interactive, immersive and walkable maps to allow users interact with cultural content, 3D models, and different multimedia content at museums and heritage sites. Hence, the applicability of the proposed systems will not be limited to museums' indoor settings; its applicability extends outdoors at the natural location of cultural heritage assets. To this end, immersive reality technologies, interaction methods, development platforms and mapping and cloud storage services have been combined to realise the interaction method. The Walkable MxR Map allows users to interact with virtual objects via maps that are virtually projected on the floor and viewable through MxR devices, specifically the Microsoft HoloLens. The projected maps are room-scale and walkable with a potential global scalability. Besides movement-based interaction, users can interact with virtual objects, multimedia content and 3D models using HoloLens's standard gesture, gaze and voice interaction methods.

1. Introduction

The roles of immersive reality technologies, such as Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MxR), in terms of enabling engaging interaction with virtual content and enriching visiting experiences in museums and heritage sites, have been demonstrated in the past (Anthes et al., 2016; Bekele and Champion, 2019a, 2019b; Bekele et al., 2018). Similarly, VH studies and applications have highlighted the crucial roles that Human-Computer-Interaction (HCI) methods play in terms of enabling the dissemination and acquisition of cultural knowledge and significance from VH applications and digital systems implemented in museums and heritage sites (Addison and Gaiani, 2000; Adhani and Rambli, 2012; Anthes et al., 2016; Katifori et al., 2019).

Following the visible trend of immersive reality technology and HCI methods' adoption in the VH domain, the role of these technologies to enhance cultural learning in VH applications is becoming an area of interest in the domain (Caputo et al., 2016; Ibrahim and Ali, 2018; Ibrahim et al., 2011; Maye et al., 2017; McGookin et al., 2019). A recent article that attempted to compare existing immersive reality technologies and interaction methods against their potential to enable collaboration, engagement and contextual relationship in VH applications identifies MxR and collaborative and multimodal interaction methods as ideal tools for VH applications that target cultural learning (Bekele and Champion, 2019a).

The design and implementation of the interaction interface proposed as 'Walkable MxR Map' in this paper will primarily revolve around establishing the base platform for enabling collaboration, engagement and contextual relationship in VH applications, while cultural learning is placed at the centre of the whole design and implementation process. Interested readers may find the following articles for detailed discussion of cultural leaning in virtual environment, collaboration, engagement and contextual relationship (Bekele and Champion, 2019a; Ibrahim and Ali, 2018; McGookin et al., 2019; Šašinka et al., 2019; Tost and Economou, 2009). Here, it is worth it briefly discussing what collaboration, engagement, contextual relationship and cultural learning are from VH perspective.

Collaboration refers to the capability of virtual environments and interaction methods to allow either a co-located or remote collaboration between two or more users of VH applications. Collaboration can be

E-mail address: mafkereseb.bekele@postgrad.curtin.edu.au.

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considered as both an aspect of VH experience and a form of interaction method. In both cases, the collaborative environment/method mimics or it reflects users' or visitors' experience as it would be at physical museums or heritage sites. Enabling collaboration requires more than a collaborative interaction with a virtual simulation/reconstruction of cultural heritage. It also requires the implemented VH application to influence users' experiential aspects as a result of their collective actions.

Engagement relates to the ability of virtual environments and interaction methods to enable and facilitate engaging experiences as a result of a combination of spatial and contextual immersivity (3D virtual environments and meaningful content) and intuitive interaction with the cultural context in the virtual environment. To this end, VH applications rely on interaction methods, immersive headsets (VR and MxR devices), and relevant cultural context. For instance, combining a tangible interaction method with highly immersive virtual environment and a relevant cultural context can be as engaging as a physical visit in museums and heritage sites (Katifori et al., 2019). Hence, VH applications that balance cultural context, interaction and immersivity can lead to enhanced cultural learning.

Contextual relationship refers to establishing a contextual relationship between users, cultural context, and the immersive reality systems. Existing VH applications that adopt immersive reality technologies for cultural knowledge dissemination focus on users' interaction with the VH applications (Caggianese et al., 2018; Brett Ridel et al., 2014a,b; Schaper et al., 2017; tom Dieck and Jung, 2017). However, in order for VH applications to enhance cultural learning, establishing a contextual relationship between users, their physical surroundings (museums and heritage sites), and the virtual environment (cultural content) is as crucial as enabling intuitive interaction with the virtual environment. Hence, the relationship factor can be further categorised into three: relationship between user and reality (User-Reality relationship), relationship between user and virtuality (User-Virtuality relationship), and relationship between reality and virtuality (Reality-Virtuality relationship). An ideal immersive reality scenario will combine these elements into a User-Reality-Virtuality (URV) relationship (Bekele and Champion, 2019b).

The central objective of the interaction interface 'Walkable MxR Map' is, therefore, to propose and implement a base platform that can be adopted by the VH studies that target at balancing/integrating collaboration, engagement and contextual relationship as crucial interaction design elements of VH applications. As such, this paper reports on the details of the design and implementation of the interface.

At a high-level view, the proposed interface is a map-based interaction method in a Mixed Reality (MxR) environment. The interaction method is implemented by combining immersive reality, mapping and cloud storage services, and immersive reality application development platforms. The interaction method enables users to interact with virtual content via interactive and walkable virtual maps projected on or around the user's immediate surrounding. The maps serve as interaction metaphor, gateway to linked digital records of artefacts, and stage for presenting virtual content such as 3D models and audio-visual multimedia content relevant to a specific cultural or historical context in a museum environment and heritage sites. Hence, geospatial information sources (mapping services), engagement, and interactivity are the crucial interaction design aspects/elements of the map-based interaction method. The contributions of the Walkable MxR Map to the VH domain are summarised as follows:

(A) The application enhances visiting experience at museums and heritage sites. Conventional museums and heritage sites don't allow physical manipulation of artefacts. In such cases, users acquire further information about the artefacts through printed media and digital multimedia content displayed on screens next to the artefacts. The Walkable MxR Map, however, will enable users to manipulate the digital representations of the artefacts (3D models) via interactive and immersive MxR visualisation environment.
(B) The approach will be an addition to the fairly new application category (theme) of the VH domain that attempts to adopt and disseminate immersive reality technologies for the promotion of cultural learning.
(C) The implementation of this approach contributes towards extending the existing expertise that tackles the technical challenges of combining geospatial information and immersive reality technologies across various domains.
(D) The proposed approach will serve as an initial platform for cultural learning themed VH application that attempt to combine cloud services, multiple geospatial and multimedia sources, immersive reality and interaction interfaces.

The remainder of the paper is organised as follows. Section 2 will discuss existing and related studies and VH applications. Section 3 and 4 will provide detailed discussion on the design, system components and architecture of the proposed interaction interface and its prototypical implementation along with technological aspects and requirements. Finally, Section 5 and 6 will discuss and conclude the results of the prototypical implementation, limitations of the approach and areas of improvement for future works to extend the applicability of the Walkable MxR Map.

2. Related works

Immersive reality technologies play an important role in cultural heritage and education (cultural learning). These technologies can enhance visitors/users' interest, attention and engagement in museums and heritage sites. For instance, De Paolis et al. (2018) leverage AR to help students understand spatial concepts and the working principles of complex mechanical components of machines designed by Leonardo Da Vinci. The authors use a mobile augmented reality application that shows the overall structure and the working principles of some machines recognized on the pages of the Atlantic Codex in a form of virtual models superimposed over Leonardo's sketches framed by the camera of mobile devices. Girão et al. (2018) present a markerless multi-view vision-based system to create a spatial representation of an indoor environment to achieve the virtualization of a room and its elements, providing seamless user navigation and interaction, which can be used as the base virtual environment for interactive virtual visits to heritage sites museums.

Following the increasing availability and accessibility of immersive reality technologies, museums have shown interest in exhibiting a representation of cultural heritage assets using different multimedia approaches. However, existing museums that keep adopting traditional exhibition fail to attract the visitors' interest continuously as such approaches provide only static and non-interactive contents. Recently, high performance measurement techniques have rapidly developed to a degree that allows for the realistic digitization of cultural heritage assets (Yong Yi Lee et al., 2015). Such digitisations of cultural heritage allow the creation of dynamic and interactive content, such as 3D video and augmented reality, which will improve the visitors' experience in virtual environments. However, an effective communication of cultural content requires more than a dynamic content creation; the platform where the content is presented and how users interact with the content are crucial aspects that determine the effectiveness.

One of the main features of the virtual environments used for cultural heritage content dissemination is the spatial dimensionality of the VH application. When we think about spatial dimensionality in virtual environment, we usually refer to 3D models and panoramic video. However, these are not the only existing channel of representing the physical environment from a spatial perspective. 3D or spatial audio and geospatial content (maps) extend the dimensionality of virtual 3D environments. For instance, D'Auria et al. (2015) present a cloud based interaction system based on spatialized sounds. The developed application was used as a personal guide, in 3D sound, attracting the tourists' attention toward monuments or buildings.

In the past, studies in the geospatial technology domain have attempted to integrate geospatial information and AR (Maiwald et al., 2019; St-Aubin et al., 2010, 2012). For instance, a framework introduced by Wüest and Nebiker (2017) attempted to combine geospatial tools and smartphone-based AR in order to augment large-scale walkable maps (printed) and orthoimages in museums or public spaces. This specific approach uses orthoimage mosaic prints placed on the floor covering several hundred square meters. The primary objective of the maps and orthoimages is serving as markers for the AR application. The AR application allows users to interact with digital content relevant to specific historical aspects of locations identified on the orthoimages. Nevertheless, users' experience scale is limited to the environment (physical space) where the orthoimage mosaics are placed, meaning the AR application always relies on the extant of those physical maps and orthoimages. In addition, the number of visitors that can use the application at a given time is also limited to the capacity of the physical space.

St-Aubin et al. (2012) highlight the potential use of Geospatial Augmented Reality (GAR) for interaction and visualisation of geospatial data. The authors identify the approach as an alternative solution to overcome the limitations of existing geospatial design tools. For instance, the sophisticated interaction interfaces visible in GIS and CAD tools are not easy to understand for non-expert users. Aiming at overcoming such limitations, the authors' attempt to design and implement a Geospatial AR application for specific designing tasks in urban environments. Similarly, a recent study that specifically targeted urban excavation tasks adopts Geospatial AR as a knowledge-base and enabling tool for excavation workers to visualise and monitor the proximity between invisible utilities and digging implements (Su et al., 2013). An interesting aspect of this application is its ability to capture the uncertainty in geospatial information and overlay it into the AR view. Another related set of applications and services are provided by vGIS project,[1] among a number of features, it offers full 3D holographic maps using HoloLens incorporating data from multiple providers.

In general, immersive reality applications that are flavoured with a spatial aspect fall into two categories, namely Spatial Augmented Reality (SAR) and Geospatial Augmented Reality (GAR). The distinction between SAR and GAR is that the former augments real world objects and scenes without the use of monitors, Head-Mounted-Display (HMD) or Hand-Held-Devices (HHD). SAR makes use of digital projectors to display graphical information onto the physical environment or physical objects (Bekele et al., 2018; Carmigniani et al., 2011). GAR, on the other hand, is location-based AR that relies on geospatial information to determine the pose of virtual elements. From a technological point of view, GAR can use any of AR or MxR display technologies that fit the technical and experiential requirements of overlaying graphical elements over the real world or merging them with georeferenced virtual environments. All in all, SAR is a specific category of immersive reality display technology, whereas GAR is a specific implementation or approach of AR that explicitly relies on geospatial information to determine the pose of virtual elements.

Donato Maniello (2018a,b) presents a Spatial Augmented Reality technique that targets scale models of archaeological finds and cultural heritage. The presented technique offers new communication method for archaeology and museum sites to disseminate cultural context of fragile, destroyed or distant assets from their exhibition site to be reached by wider audience. Hence, the approach increases the accessibility of cultural heritage assets via VH application that leverages SAR technology.

GAR applications or a combination of geospatial tools and Augmented Reality (AR) technologies, are exploited in the Cultural Heritage (CH) domain (Bollini and Falcone, 2012; Fogliaroni, 2018). However, immersive reality applications that adopt AR or SAR display technologies are relatively common in the literature (Favre-Brun et al., 2012; Y. Y. Lee et al., 2015a,b; D. Maniello, 2018a,b; Palma et al., 2018; B. Ridel et al., 2014a,b; Rossi, 2019) than Geospatial AR. A recent study (Maiwald et al., 2019) that introduces three types of GAR implementations (a 3D WebGIS application, VR and AR) attempts to create a research environment/platform that provides art historians with access to historical photography of urban architecture. For instance, the WebGIS application[2] integrates 3D/4D (3D models with additional temporal dimension) assets with historical photographic documents related to specific urban architecture (see Fig. 2). Furthermore, the fully immersive VR as well as handheld AR applications mentioned above were used in a museum to allow users to perform a free exploration of historical photography in a spatial setting (see Fig. 1). All the three implementations are alternatives to the conventional ways of accessing large scale repositories of historical photographs. On top of that, the applications rely on geospatial information or the geographic location and orientation of the photographs to access them from the repository.

The Walkable MxR Map proposed in this paper shares some characteristics from both SAR and GAR. Firstly, the characteristic it inherits from SAR is that users perceive virtual objects merged and projected onto the physical environment and physical objects. However, unlike SAR, the virtual objects in the Walkable MxR Map can be viewed only via HMDs. SAR, on the other hand, allows users to see virtual elements without the use of HMDs. Secondly, the Walkable MxR Map inherits GAR's distinctive reliance on geospatial information. These properties make the Walkable MxR Map an ideal candidate for museums and cultural heritage sites, because it can enrich visiting experience with immersive, engaging, informative and interactive virtual elements. In addition, the use of virtual maps assists users to quickly understand location related historical and cultural aspects of artefacts. Users can interact with a virtual 3D recontraction of artefacts and additional multimedia content that complement the experience can be presented on the map. This can indirectly enable users to interact with artefacts and assets in museums and heritage sites that are otherwise inaccessible to the general public for physical manipulation.

3. System architecture and components of the walkable MxR map

The Walkable MxR Map has five major components: Head-Mounted-Display, Geospatial Information and Event Cue, Interaction Inputs and Mixed Reality (MxR) Framework, Event and Spatial Query Handler, and Cultural Dataset containing historical and cultural context (3D models, multimedia content and event spatiotemporal information). Fig. 3 shows the overall system architecture and its major components. A detailed discussion on the overall architecture and on each component is presented below. The discussion focuses on the components' individual role in the architecture and their contextual relationship with other components of the system.

3.1. Head-Mounted-Display

Head-Mounted-Display (HMD) is one of the main categories of immersive reality display technologies. There are optical-see-through and video-see-through varieties of HMDs. The Walkable MxR Map uses an optical-see-through HMD, specifically the Microsoft HoloLens. HoloLens is preferred over other HMDs, such as Meta 2 and Magic Leap, because it has inbuilt processing units to handle all computational needs and it has a relatively larger community of developers. In addition, the Mixed Reality Toolkit,[3] which is a set of tools to assist the development of MxR applications for HoloLens and other Windows VR devices,[4] is

[1] https://www.vgis.io/.

[2] http://4dbrowser.urbanhistory4d.org.

[3] https://github.com/microsoft/MixedRealityToolkit-Unity.

[4] https://www.microsoft.com/en-us/store/b/virtualreality.

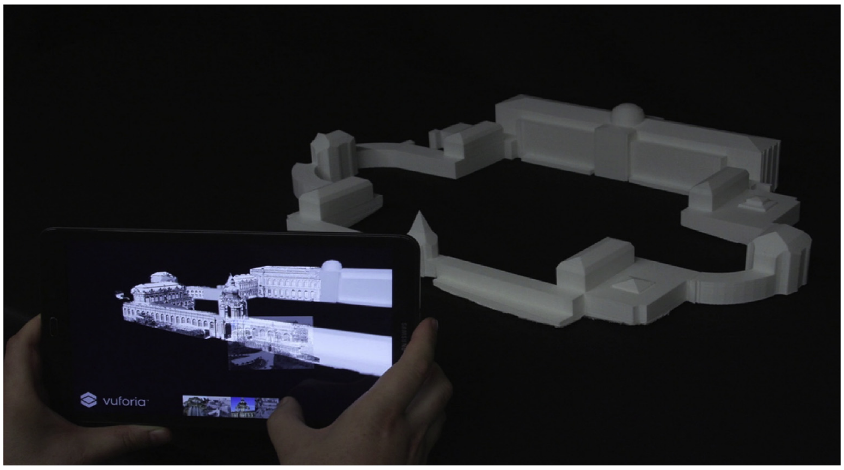

Fig. 1. Augmented Reality installation using historical photography as textures for 3D-printed model of architecture (Maiwald et al., 2019). Copyright © Authors 2019. CC BY 4.0 License.

Fig. 2. Prototype browser application of HistStadt4D with interactivity and automatically oriented images (Maiwald et al., 2019). Copyright © Authors 2019. CC BY 4.0 License.

compatible with Unity game engine. This tool can also easily consume map services, such as Bing Maps and Google Maps. Such map services are the backbone of the mapping and geospatial component of the Walkable MxR Map system. However, this HMD is not affordable to the general public, museums and cultural heritage sites. Currently, the device is used in universities, research labs and enterprises. Hence, given the limited accessibility of the device, its relevance to the overall adoptability the system architecture of the Walkable MxR Map system is limited. Considering this legitimate concern, this paper will suggest reasonably cheaper alternatives.

The HMD functions as a display, computational unit, and interaction input device. For instance, when the Walkable MxR Map application is launched at first, the device displays maps and places audio-visual cues on the maps and/or merge them with objects around the user. At this stage, the inbuilt interaction input sensors will actively stream gestural, movement, gaze and voice inputs into the "Mixed Reality Framework" component. Then, this component performs the required computation and either return audio-visual feedbacks to the user or send the inputs to the "Event and Spatial Query Handler" for further computation.

3.2. Geospatial Information and Event Cue

This component consists of two subcomponents, Geospatial Information and Event Cue. The Geospatial Information subcomponent is a combination of map and imagery services, specifically Bing Maps and Google Maps. The virtual maps and images that users see virtually projected on the floor and their surroundings are streamed form these map and imagery services. The Walkable MxR Map relies on the Geospatial

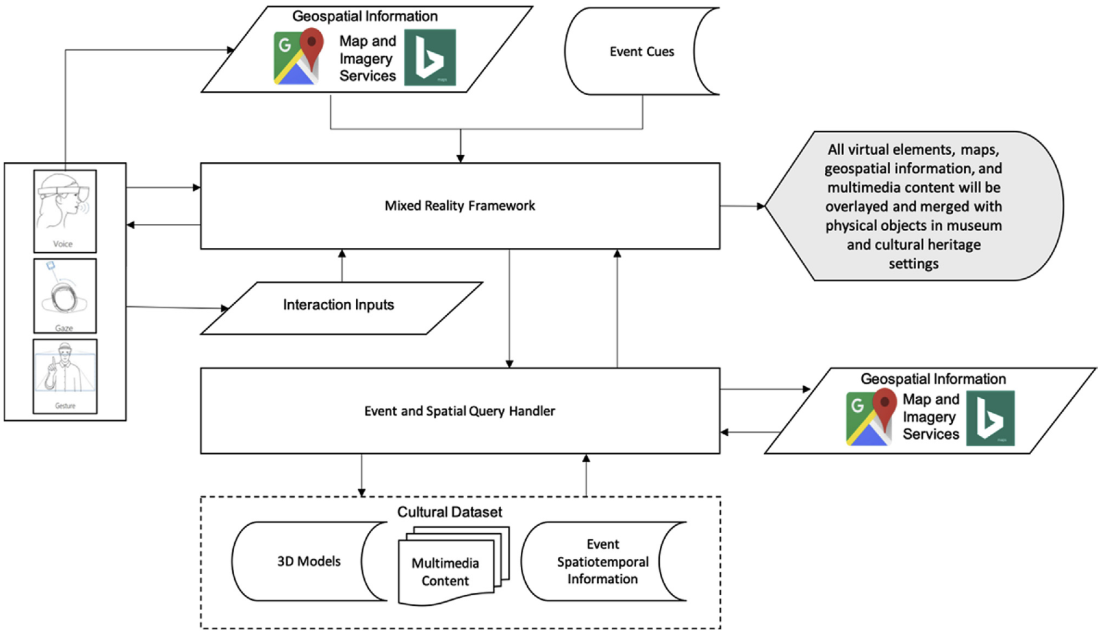

Fig. 3. System architecture of the walkable mixed reality map.

Information subcomponent to enable users' interaction with linked historical and cultural context from the Cultural Dataset component.

The Even Cues consists of audio-visual, 3D models, and textual cues that are interactable and linked to specific events of a given historical or cultural context. For instance, a Walkable MxR Map scenario that presents maritime heritage will project a historical map on the floor and Event Cue, such as textual descriptions, historical documents, and 3D reconstructions of artefacts related to the same maritime heritage, will be placed on the map and spatially aligned to their historical geographic locations. The Event Cue then functions as a gateway to a detailed historical and cultural context, multimedia content and spatiotemporal information in the Cultural Dataset component. Users will be able to interact with the Event Cue using gesture, movement, gaze and voice interaction modalities.

3.3. Interaction inputs and Mixed Reality Framework

This component is crucial to the overall system architecture. The component is a combination of two parts, namely Interaction Inputs and Mixed Reality Framework. The Interaction Inputs aspect comprises four modes of interaction; gesture, movement, gaze and voice. For instance, users will be able to interact with virtual elements and Event Cue based on their proximity to the virtual objects. This will allow to hide or reveal more content when users are within a predefined proximity zone to a certain element placed on the map. Usually, two or more modes of interaction inputs are combined to avoid a potential ambiguity. For instance, if a user is within a proximity range of more than one Event Cue, additional input (gaze, gesture or voice) will be used to determine the likely Event Cue candidate for further computation, detail revelling or displaying more content from the Cultural Dataset component. Such approach is essential to optimize the performance of the Walkable MxR Map system, because rendering multiple 3D models, multimedia content and graphical elements at once will introduce heavy workload on the device and that will impact users' experience.

The Mixed Reality Framework is a resource (memory and GPU) consuming subcomponent, because it is responsible for all of the graphical computation, processing and environmental tracking. Tracking is crucial to spatially understand the users' surrounding and continuously correct virtual assets' pose and overlay graphical content onto the user's view to the physical environment. This component communicates with most parts of the overall system. For instance, it actively listens to interaction inputs, calls into the Event and Spatial Query Handler, and overlays the results back to the users' view.

3.4. Event and Spatial Query Handler

The Event and Spatial Query Handler has two subcomponents that are synchronised with the Cultural Dataset and Spatial Information components. The first subcomponent, Event Handler, is responsible to handle manipulation tasks, such as scaling, rotating and moving virtual objects. Based on the type of events perceived by the Event Handler, additional content will be accessed from the Cultural Dataset and presented to the user through the Mixed Reality Framework. For instance, if a virtual object (3D model) is scaled up for a zoomed in view, more content from the Cultural Dataset and a larger scale map from the Geospatial Information components will be streamed to the users view along with 3D models and multimedia content from the Cultural Dataset.

The second subcomponent, Spatial Query Handler, has two main roles. First, it functions as a conversion tool to convert geographic coordinates to Unity game engine coordinates and vice versa. This is a very crucial function to overlay virtual objects and events on their exact geographic coordinates. Existing game engines such as Unity don't support importing/exporting geospatial information into the development environment. Hence, the Spatial Query Handler will manage all the coordinate conversions required to make spatial queries into the Cultural Dataset and Geospatial Information components. The second role of this component is calling to the mapping services, such as Bing Maps and Google Maps, and querying the Cultural Dataset for more content based on spatial/spatiotemporal parameters received from the Event and Spatial Query Handler.

3.5. Cultural Dataset

This component is a storage for a collection of historical and cultural context, 3D models, multimedia content and event spatiotemporal information. The component plays a significant role for optimising the performance of the Walkable MxR Map system. Instead of displaying/ overlaying all content and assets at launch time, fewer assets will be displayed in the initial scenes and more information and assets will be accessed from this component based on users' interaction input and requests passed from the Mixed Reality Framework through the Event Spatial Query Handler. There are three types of assets in this component; 3D models, multimedia content, and event spatiotemporal information. The 3D models are pre-generated 3D representations or reconstructions of heritage assets or artefacts. Multimedia contents are a combination of audio, video, or digitised historical and cultural context such as historical documents, maps, drawings and photographs. Event spatiotemporal information is a set of structured datasets that record the where and when of events linked to a given cultural context. This type of information is also used as a set of spatial query parameters by the Spatial Query Handler.

4. Implementation of the walkable MxR map as interaction interface for Virtual Heritage

The system architecture discussed above was implemented using a commercial wearable device (HMD), proprietary software, opensource toolkits, and custom-written scripts. This section will discuss these tools, technologies and limitations encountered during the implementation.

The discussion that focuses on the limitations associated with the adopted tools and technologies might be useful to readers interested in adopting the system architecture across domains and diverse application areas. As such, the sections below will present a high-level discussion on the full potential of the technologies, devices and tools that were explored in this paper, and a detailed discussion on the portion of those tools employed by the system will also be provided.

4.1. Microsoft HoloLens

Microsoft HoloLens is a self-contained Head-Mounted-Display (HMD) that runs on Windows Mixed Reality operating system developed by Microsoft (see Fig. 4). Currently, there are two generations of this device: HoloLens 1 and HoloLens 2. The implementation of the Walkable MxR Map was performed using HoloLens 1. Hence, all appearances of the term 'HoloLens' refer to HoloLens 1. This device has all the resources required for tracking, computation and displaying virtual objects and audio-visual elements. Most HMDs that are currently available in the market rely on high-end VR-ready computers for computation, meaning they always have to be physically attached to computing resources or at least connect wirelessly. HoloLens, however, handles all computations using the processing units (CPU and GPU) imbedded in the device. Hence, the device can be used in different environmental conditions in both indoor and outdoor settings. As such, a potential applicability or the Walkable MxR Map in both and indoor and outdoor settings is presented in Section 5.1 and Section 5.2, respectively.

Fig. 4. Microsoft HoloLens 1.

Table 1 presents the features of HoloLens along with the required (used) features by the Walkable MxR Map system and example scenarios of experiences. The main features of HoloLens or any other immersive reality HMDs can be categorised into four enabler groups: tracking, experience scale, interaction, and spatial awareness. Each of these aspects are discussed below.

- Tracking refers to the use of either marker-based or markerless mechanisms to determine the pose of users' viewpoint or the pose of virtual elements in a given virtual environment. HoloLens follows a markerless tracking approach using four environmental understanding cameras that are inbuilt in the device itself. The Walkable MxR Map uses the default tracking mechanism to place virtual objects onto the environment and enable interaction between users and virtual objects.
- Experience scale is the spatial extent of the experience and the Degrees of Freedom (DoF) that a virtual object can move within a given virtual environment. HoloLens can enable orientation only, seated, standing, room-scale and world-scale experiences allowing a broad range of user experiences, from 360-degree video view that just need the headset's orientation, to full world-scale applications, which need spatial mapping and spatial anchors. The Walkable MxR Map uses the room-scale and world-scale capabilities to enable interaction with users and virtual objects at different experience levels.
- Interaction refers to the aspect of the HMD that enables interaction with users and the virtual environment in any immersive reality settings. Interaction methods enable users to perform common actions such as selection, manipulation and navigation. HoloLens achieves interaction via gaze, gesture and voice commands. Gaze resembles selection in conventional computer systems. Hence, gaze should always be combined with either gesture or voice input to complete the required manipulation of navigation actions. The

Table 1
Cheaper AR/MxR headsets.

Device	Features	Price	Applicability to the Walkable MxR Map
HoloKit[a]: Cardboard-like AR/ MxR headset powered by smartphone 	Compatible with iPhone and Android via ARKit, ARCore and Tango It is a see-through headset that allows seeing the real world as it is, and in the meantime virtual objects are projected on the real world	$35.00	Limited applicability due to its limited interaction inputs The headsets can be used for AR/ MxR experiences with limited interactivity that allows only visualising virtual objects merged with the physical environment
Vufine AR Kit[b]: AR headset powered by smartphone 	Compatible with most AR capable smartphones	$9.99	The full experiential aspect of the Walkable MxR Map may not be implemented on these headsets, however, the headsets can be used with a customised system architecture that allows substituting the projected maps with printed maps
HRBOX2 AR: AR headset powered by smartphone 	Compatible with most AR capable smartphones	$67.99	

[a] https://holokit.io/.
[b] https://www.vufine.com/vufine-ar-kit/.

Walkable MxR Map uses all the three forms of interaction inputs (gaze, gesture and voice) along with movement, meaning users can interact with virtual objects by combining gaze and their proximity to the virtual object.
- Spatial awareness is the ability of the HMD to continually understand the pose of users and virtual objects relative to physical objects and the physical environment itself. HoloLens uses spatial mapping, spatial anchor and spatial sound to enable virtual objects and users, to some extent, determine their relative position in the environment. To this end, the device's environmental understanding cameras and its capability to simulate 3D sound using direction, distance and environmental simulations are used to determine relative positions in the virtual environment. The Walkable MxR Map relies on the spatial awareness aspect to inform the pose of virtual objects to users.

Even though Microsoft HoloLens combines all the computational and technological requirements to achieve the aspects discussed above, its expensive price tag ($3,500) makes it a less favourable HMD for VH applications in museums and heritage sites. Hence, this paper highlights affordable AR/MxR headsets that can be used to implement a customised version of the Walkable MxR Map system with a limited interactivity. Table 1 presents affordable headsets with their features and applicability to the Walkable MxR Map.

4.2. Development platforms and toolkits

The Walkable MxR Map system was implemented using Unity 2018.4.x, Mixed Reality Toolkit v2.0.0 Release Candidate 2.1 (MRTK v2.0.0 RC2.1) and Microsoft Visual Studio 2017. Unity is a game engine that provides multiplatform support for building games. Currently, Unity supports more than 25 platforms. This game engine was used as the main development framework for the coding and implementation of the prototype of the Walkable MxR Map application. MRTK is a Microsoft driven open source tool that provides a set of foundational components and features to accelerate MxR developments in Unity. The latest version of MRTK supports a wide range of platforms, such as Microsoft HoloLens 1 and HoloLens 2, Microsoft Immersive Headsets, Windows Mixed Reality Headsets, and OpenVR headsets (HTC Vive/Oculus Rift). The toolkit was used for the basic building blocks of the Walkable MxR Map for Unity development on HoloLens. Thanks to this toolkit, rapid prototyping via in-editor simulation that allows to see changes immediately, was achieved. In addition, the toolkit is extensible to swap out core components and extend the framework. Once the development was ready for use on HoloLens, Microsoft Visual Studio 2017 was used for debugging and deploying the code from Unity to HoloLens. Interested readers can refer to Rahaman et al. (2019) for a step by step workflow of deploying MxR applications from Unity to HoloLens using MRTK and Microsoft Visual Studio 2017.

4.3. Bing Maps and Google Maps APIs

Bing Maps and Google Maps are web mapping services provided by Microsoft and Google, respectively. These services offer satellite imagery, aerial photography, street maps, 360° panoramic views of streets, real-time traffic conditions, and route planning for traveling. The Walkable MxR Map system uses these services for the implementation of the Geospatial Information component of the system. The reason behind using two mapping services is due to compatibility with the development framework and toolkit used for the implementation. For instance, the MRTK has a component that is readily available for streaming maps from Bing Maps to Microsoft Immersive Headsets. Hence, in such cases it is much efficient to use a mapping service that the toolkit has been tuned and tested to work with. When it comes to creating a custom script to stream maps to HoloLens for specific uses, both mapping services can be used. However, Google Maps was found to be an idea service since it's spatially reach and provides easy to use APIs to request the service for static and dynamic maps.

The Walkable MxR Map uses Google Maps for geospatial information or maps that appear on the initial scenes of the experience. However, once users started engaging and interacting with the maps, the Event and Spatial Query Handler component will call into the both the Bing Maps and Google Maps services to stream static maps and terrain data back to the users view. A design decision was made to separate the roles of these mapping services in order to optimize performance and effectively use the free API calls both services provide.

4.4. Unity coordinate to geographic coordinate conversion and vice versa

One of the challenges of working on MxR applications that rely on geospatial information is the lack of tools or packages that can translate real-world coordinates to Unity coordinate system. This is problematic if the application requires translating geospatial information into Unity and from Unity to other platforms. Lack of tools to handle such translations is perhaps one of the major limitations of Unity. The platform is created mainly for real-time game development that rely on the platform's coordinate system. Hence, the majority of the games that require real-world maps or any form of geospatial information as a base game asset use external tools or custom scripts to manage importing spatial content from mapping services. However, even such tools do not reveal the original real-world coordinates that are translated to Unity coordinates. The original real-world coordinate values and their translations are crucial for the Walkable MxR Map system to handle spatial queries, make API calls to mapping services and place the results back to the virtual environment. Hence, a custom script had to be developed to handle the translation between world and Unity coordinate systems. The script handles the translation by converting one range of numbers (latitude/longitude) to another (Unity coordinate as x, z values) while maintaining the ratio.

4.5. Amazon web services simple storage service (AWS S3) to store Cultural Dataset

AWS S3 is a cloud-based object storage service. This service is used as a backbone for the Cultural Dataset component of the system. Isolating the Cultural Dataset storage from the storage onboard of the HoloLens enhances the performance of the application at run time since the memory required for the application will be significantly reduced.

5. Discussion

The implementation of the Walkable MxR Map was realised using the technologies and services discussed above. This section will provide discussion on the actual prototype, expected experiential aspects, and limitations encountered during the implementation.

Fig. 5 shows a virtual map projected on the floor along with Event Cues and 3D models. It is possible to interact with the virtual environment via gaze, gesture, voice, and movement. The map covers an area of two square meter. However, users have full control of increasing the area of coverage up to four times its size based on availability of larger space for the experience. This map loads at the initial scene of the Walkable MxR Map that will be launched based on users' request. Once users start interacting with the virtual environment, a series of maps and 3D models and cultural context will be revealed to the user. For instance, Fig. 6 and Fig. 7 show 3D models placed on the map that users can manipulate and interact with.

The implementation of the Walkable MxR Map has attempted to utilise the potential of Microsoft HoloLens. There have been some limitations that prevented the system from exploiting the full potential of this device. One of the major limitations is that the development frameworks, such as MRTK, are still going through rapid and frequent changes, which sometimes causes issues related to incompatibility with existing implementations and requires extra effort to port older version codes to latest version development framework. Another challenge is that most 3D

Fig. 5. A virtual map projected on the floor. Users can see and interact with the map using HoloLens.

Fig. 6. User interacting with the Walkable MxR Map.

models in the VH domain are too detailed with complex geometry since they are meant to represent heritage assets. Rendering detailed 3D models in HoloLens is problematic. For instance, the geometry of the 3D models in Figs. 6 and 7 had more than 2 million triangles originally. In order to optimize performance, the models had to be decimated to collapse the models to a less detailed and simplified geometry.

Another limitation of the Walkable MxR Map is performance degradation due to occlusion. The MRTK framework allows developers to decide whether occlusion should be enabled or not. In general, one of the key experiential aspects that differentiates MxR from VR is that the former occludes virtual or physical objects from the other. Since the central objective of the system is a Mixed Reality experience, occlusion had to be applied to the Walkable MxR Map to enable interaction between virtual and physical objects. This, however, puts extra workload on

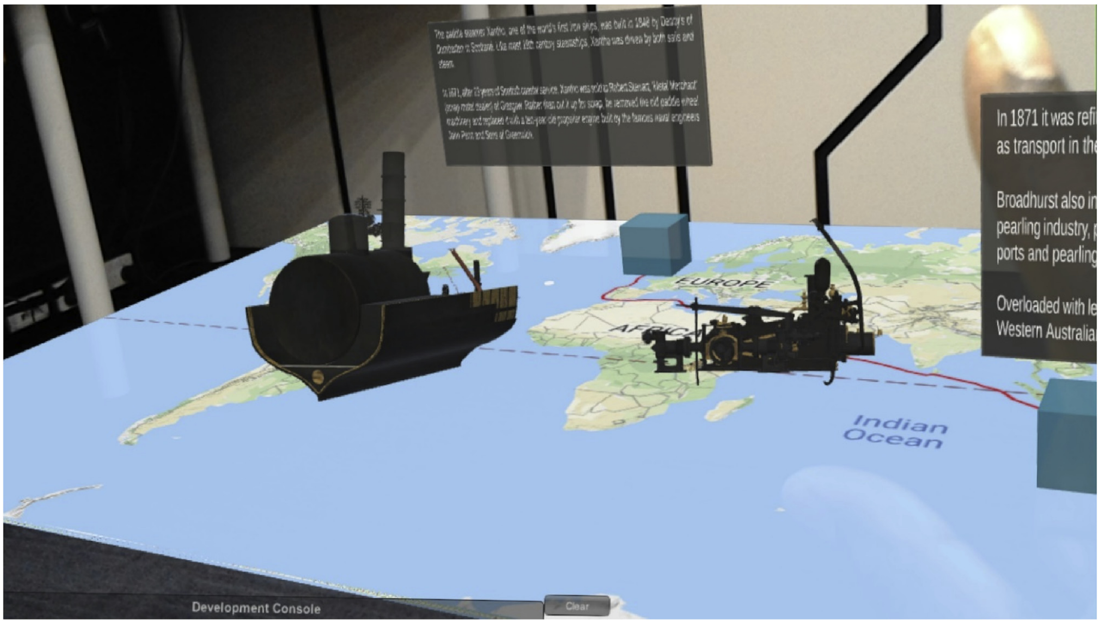

Fig. 7. User moving round the map projected on the floor and interacting with 3D models placed on the map.

the device, especially when there are moving objects continually detected by the environmental understanding cameras of the device. As a result, some lags were introduced when rendering frames.

The Walkable MxR Map has the potential to be applied to VH application under both indoor and outdoor settings. The sections below discuss scenarios on how the prototype can be used or extended to meet such settings.

5.1. Applicability of the system – indoor settings

Conventional museums and heritage sites don't allow physical manipulation of artefacts. In such cases, users acquire further information about the artefacts through printed media and digital multimedia content displayed on screens next to the artefacts. The Walkable MxR Map, however, will enable users to manipulate the digital representations of the artefacts (3D models) via interactive and immersive MxR visualisation environment.

The Walkable MxR Map provides the chance for visitors/users to indirectly interact and manipulate with artefacts through the digital representations.

Another role the Walkable MxR Map can play, given the current conventional museum setup, is enabling contextual relationship between artefacts in museums. For instance, when users start interacting with a given artefact, the application can easily identify other artefacts in the museum that are semantically, spatially or temporally related to the artefact that users are interacting with. This enhances users' visiting and learning experience since the cultural context presented to users is dynamic and interactive that is influenced mainly by users' interaction with the application, rather than a linear information presentation format predetermined by curators and cultural heritage professionals.

5.2. Applicability of the system – outdoor settings

The Walkable MxR Map has a potential to be applied outdoors. Two scenarios have been identified. First, the same applicability of the application under indoor settings can be replicated outdoors. Meaning, multimedia content relevant to cultural heritage assets can be streamed to users at heritage sites. In addition, the walkable maps can be used to guide users through different cultural assets at a given heritage site. In such cases, the displayed maps need to be at a world scale and efficient tracking method is required to enable occlusion and overlay virtual objects (cultural content) onto users' view to the physical environment. The Walkable MxR Map can be adopted to such scenario with minimum effort and customisation, which basically involves changing the scale of the experience from room scale to world scale (See Table 2 for detailed experiential aspects of the system).

Second, the application can be used to enable collaborative experience between curators located in museums and remote visitors/users wandering at heritage sites or vice versa. Curators in the museum can communicate and collaborate with the remote visitors to provide guidance. However, this scenario will require architecture level changes to the system architecture presented in this paper. To this effect, an architecture level improvement and extension has been identified as a key future work. Hence, extending the interaction spectrum of the Walkable MxR Map towards a multimodal and collaborative interaction space will be the focus of future works.

6. Conclusions

A novel map-based interaction interface, namely Walkable MxR Map, has been proposed and implemented in this paper. The central objective of the application is enhancing cultural learning in VH applications by enabling a contextual relationship and interaction between users, immersive reality technologies and cultural context. To this end, a system architecture consisting of five components has been proposed. In addition, a working prototype has been built using custom, proprietary and commercial resources. The implementation phase has led to identifying key limitations, such as performance degradation when occlusion is applied, and geometrically complex 3D models are used as assets. Furthermore, the potential applicability of the system under indoor and outdoor settings have been identified and discussed.

Future works will attempt to propose and implement solutions to the

Table 2
Features of the Microsoft HoloLens and their contextual uses for the Walkable MxR Map system.

Features	HoloLens (1st gen)	Walkable MxR Map requirements	Example experience
Experience scale	HoloLens can enable orientation only, seated, standing, room scale and world scale experiences	The system requires room scale experience for the map and world scale experience for virtual elements (3D models) merged with the environment	Room scale experience allows users walk on and around a virtual map overlayed on the floor World scale experience enables 3D models interact with the environment when manipulated or replaced by users Users can wander beyond an area about 5 m
Gaze Interaction	Gaze is the primary form of targeting in HoloLens Gaze informs MxR applications where the user is looking in the world	The system relies on gaze input to determine when the users are looking on the map and around the room	Users look at an Event Cue to reveal linked content from the Cultural Dataset Users look at specific location on the map or look at 3D models to initiate manipulation, scaling and replacement functionalities Users combine gaze and gesture or voice to interact with virtual elements
Gesture Interaction	Hand gestures allow users to action in MxR Interaction is built on gaze to target and gesture or voice to act upon whatever element has been targeted The core gestures of HoloLens air tap and bloom Air tap is a tapping gesture with the handheld upright, similar to a mouse click or select. Bloom is the "home" gesture and is reserved for that alone Composite gestures are used for manipulation and navigation Manipulation gestures can be used to move, resize or rotate a virtual object Navigation gestures operate like a virtual joystick, and can be used to navigate UI widgets, such as radial menus	Walkable MxR Map uses gesture to allow users interact with virtual elements that they are gazing at	Users look as a 3D model and rotate the object using manipulation gesture (air tap and drag) Users look at virtual objects and scroll through a collection of multimedia content relevant to a given historical or cultural context
Voice Interaction	Voice interaction allows users to directly command a virtual object without having to use gestures Users can simply gaze at a virtual object and speak a command (keywords)	The Walkable MxR Map relies on voice input for some specific actions, such as initiating a spatial request to the Geospatial Information component	Users gaze at a specific Event Cue on the map and speak a keyword "more detail" and the Mixed Reality Framework displays items from the Cultural Dataset and Geospatial Information components
Spatial Mapping	Spatial mapping provides a detailed spatial representation of the real-world surfaces in the environment around the user (HoloLens) Spatial mapping is commonly used for object placement, occlusion, physics and navigation	The system relies on spatial mapping to determine the coordinate for placement of virtual objects Virtual objects' behaviour when interacting with the environment will be determined using spatial mapping	Users interact with virtual objects and the objects obey physics and occlusion, for instance, the object always remains above the floor and won't pass through walls
Spatial Sound	Spatial sound simulates 3D sound using direction, distance, and environmental simulations	The system uses spatial sound to inform users the location of objects that are out of our line of sight	Users use spatial sound to guess where an Event Cue (audio-visual cue) is located

key limitations mentioned above. In addition, extending the interaction spectrum towards a multimodal and collaborative interaction space will be the focus of future works. This will require modifying the architecture to combine Azure Spatial Anchor, image recognition, computer vision algorithm services from Microsoft Azure. These services have the potential to enable a robust tracking solution that will contribute towards enhancing the performance of the Walkable MxR Map system. Moreover, the multimodal and collaborative interaction aspects will enrich users' experience by enabling collaboration and interaction between users.

Declaration of competing interest

I declare that there is no conflict of interest.

I Mafkereseb Kassahun Bekele declare that there is no conflict of interest and I am the sole author of this submission.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.daach.2019.e00127.

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Chapter 7

Clouds-Based Collaborative and Multi-Modal Mixed Reality for Virtual Heritage

Publication review:

1. Extends the “Walkable Mixed Reality Map” to include collaborative and multi-modal interaction methods.
2. Designs and implements a novel approach that integrates cloud computing, mixed reality and virtual heritage.

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Article

Clouds-Based Collaborative and Multi-Modal Mixed Reality for Virtual Heritage

Mafkereseb Kassahun Bekele

School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University, Perth, WA 6102, Australia; mafkereseb.bekele@postgrad.curtin.edu.au or mafkereseb@hotmail.com

Abstract: Recent technological advancements in immersive reality technologies have become a focus area in the virtual heritage (VH) domain. In this regard, this paper attempts to design and implement clouds-based collaborative and multi-modal MR application aiming at enhancing cultural learning in VH. The design and implementation can be adopted by the VH domain for various application themes. The application utilises cloud computing and immersive reality technologies. The use of cloud computing, collaborative, and multi-modal interaction methods is influenced by the following three issues. First, studies show that users' interaction with immersive reality technologies and virtual environments determines their learning outcome and the overall experience. Second, studies also demonstrate that collaborative and multi-modal interaction methods enable engagement in immersive reality environments. Third, the integration of immersive reality technologies with traditional museums and cultural heritage sites is getting significant attention in the domain. However, a robust approach, development platforms (frameworks) and easily adopted design and implementation approaches, or guidelines are not commonly available to the VH community. This paper, therefore, will attempt to achieve two major goals. First, it attempts to design and implement a novel application that integrates cloud computing, immersive reality technology and VH. Second, it attempts to apply the proposed application to enhance cultural learning. From the perspective of cultural learning and users' experience, the assumption is that the proposed approach (clouds-based collaborative and multi-modal MR) can enhance cultural learning by (1) establishing a contextual relationship and engagement between users, virtual environments and cultural context in museums and heritage sites, and (2) by enabling collaboration between users.

Keywords: mixed reality; cloud computing; virtual heritage; collaborative interaction; multi-modal interaction

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1. Introduction

Interactive digital technologies, alongside various interpretive multimedia approaches, have recently become a common appearance in traditional museums and cultural heritage sites. These technologies are enabling museums to disseminate cultural knowledge and enrich visitors' experiences with engaging and interactive learning. Studies have also shown that collaboration, interaction, engagement, and contextual relationship are the key aspects to determine the effectiveness of virtual reality applications from a cultural learning perspective [1–5].

Specifically, immersive reality technologies, such as augmented reality (AR), virtual reality (VR), and mixed reality (MR) enable the creation of interactive, engaging, and immersive environments where user-centered presentation of digitally preserved heritage can be realised. Cultural heritage, more specifically the VH domain, has been utilising these technologies for various application themes [6]. For instance, the ARCHEOGUIDE is a typical example of one of the earliest adoptions of the technology with a well-defined goal of enhancing visitors' experience at heritage sites [7].

Interaction with virtual content presented in VH applications is an essential aspect of immersive reality that has a defining impact on the meaningfulness of the virtual environment. In this regard, studies in the VH domain have demonstrated how interaction methods play a role in terms of enhancing engagement, contextual immersivity, and meaningfulness of virtual environments. These characteristics are crucial aspects of interaction in VH for enhancing cultural learning. There are six interaction methods that VH commonly adopt: tangible, collaborative, device-based, sensor-based, hybrid, and multi-modal interfaces [8]. Collaborative interfaces often use a combination of complementary interaction methods, sensors, and devices to enable co-located and/or remote collaboration among users. Multi-modal interfaces are a fusion of two and more sensors, devices, and interaction techniques that sense and understand humans' natural interaction modalities. This interface group allows gestural, gaze-based, and speech-based interaction with virtual content. Combining collaborative and multi-modal interaction methods with MR allows multiple users to interact with each other (social presence) and with a shared real-virtual space (virtual presence). This combination, therefore, results in a space that enables collaboration and multi-modal interaction with the real-virtual environment, thereby resulting in a scenario where both social and virtual presence can be achieved. The interaction method proposed in this paper, therefore, attempts to bring collaborative and multi-modal MR to museums and heritage sites so that users will be able to interact with virtual content at the natural location of the heritage assets that are partially or fully represented in the virtual environment.

Some of the technical obstacles that immersive reality applications face include the cost associated with owning the technology, computational and rendering resources, and the level of expertise required to implement and maintain the technology and its underlying infrastructure. This paper, therefore, proposes to utilise cloud computing to tackle these difficulties.

The application proposed in this paper "clouds-based collaborative and multi-modal MR" introduces a novel approach to the VH community, museum curators, and cultural heritage professionals to inform the practical benefits of cloud computing to function as a platform for the implementation of immersive reality technologies. The novelty of this approach is that it integrates cloud computing, multiple interaction methods and MR while aiming at cultural learning in VH. Here, we would like to note the deliberate use of the term "clouds" in a plural form to signify that the application attempts to utilise cloud services from multiple providers. The proposed application is motivated by: (1) cloud computing technology's ability for fast development/deployment and elasticity of resources and services [9], (2) the ability of collaborative and multi-modal interaction methods to enhance cultural learning in VH as demonstrated by the domain's existing studies, for instance [10], and (3) the continuous improvement of natural interaction modalities and MR devices. The contributions of the application are, therefore:

Ultimately, the success of a VH application is determined by its effectiveness to communicate the cultural significance and values of heritage assets. Enhancing this knowledge communication/dissemination process is the primary motivation behind the proposed application. Hence, this paper contributes to VH applications, especially where cultural learning is at the centre of the application design and implementation process.

Cloud computing is a relatively new area in computing. As a result, it is not common to find cloud-based systems and applications in the cultural heritage domain. Similarly, cloud-based immersive reality applications are rare in VH. This paper, therefore, serves as one of the few early adoptions of cloud computing as a platform for immersive reality implementations in VH.

Studies show that VH applications and their virtual environments are not often preserved after their implementation [11]. Cloud computing will play a major role in preserving VH applications and their virtual environments for a longer period if cloud resources are maintained for this purpose. The proposed approach will attempt to preserve both the application and digital resources via an institutional repository.

Interaction and engagement with a given virtual environment in VH determine whether users can acquire knowledge and understand the significance of cultural heritage assets that the application is attempting to communicate. To this end, the proposed application will attempt to balance interaction and engagement with the technology and cultural context through collaborative and multi-modal interaction methods.

The remainder of this paper is organised as follows. Section 2 will discuss existing literature and exemplar VH applications that mainly utilise immersive reality technology, cloud computing, and adopt collaborative and multi-modal interaction interfaces. Section 3 will provide a detailed discussion on the system architecture proposed in this paper. Following that, Section 4 will explain the implementation phase in detail from a technical perspective. Section 5 will present a discussion on the built prototype focusing on the expected impact of the application on cultural learning in museum settings and provides discussion on identified limitations of the application. Finally, Section 6 will summarise the paper and will discuss future works and provides suggestions on parts of the system architecture that need improvement.

2. Related Works

With the advent of MR, recent developments in the presentation aspect of VH show that this technology has the potential of becoming the dominant member of immersive reality technologies, especially, when the main goal of the applications under consideration is delivering an engaging and interactive real-virtual environment [8,12]. However, several technical difficulties associated with the technology are preventing it from a wider adoption across domains and application themes. One of these technical challenges is the computational resources that immersive reality devices are required to be equipped with. For instance, the resources required for mobile augmented reality applications are often available on the same mobile device. As such, mobile augmented reality applications are widely available [13–17]. On the other hand, fully immersive and interactive MR applications are difficult to find. This is because MR applications are resource-intensive. Such applications often involve heavy graphical computations, rendering, and very low latency to deliver an engaging and interactive experience to the end-user [18–21]. In this regard, serval studies have demonstrated the potential of cloud computing to meet the computational demands of various application themes in the cultural heritage domain. For instance, a recent study by Abdelrazeq and Kohlschein [9] proposed a modular cloud-based augmented reality development framework that is aimed at enabling developers to utilise existing augmented reality functionalities and shared resources. Moreover, the proposed framework supports content and context sharing to enable collaboration between clients connected to the framework. Another study by Fanini and Pescarin [22] presented a cloud-based platform for processing, management and dissemination of 3D landscape datasets online. The platform supports desktops and mobile devices and allows collaborative interaction with the landscape and 3D reconstructions of archaeological assets.

Similarly, a study by Malliri and Siountri [23] proposed an augmented reality application that utilises 5G and cloud computing technologies aimed at presenting underwater archaeological sites, submerged settlements and shipwrecks to the public in a form of virtual content. Yang, Hou [24] also proposed a cloud platform for cultural knowledge construction, management, sharing, and dissemination.

A recent study by Toczé and Lindqvist [18] presented an MR prototype leveraging edge computing to offload the creation of point cloud and graphic rendering to computing resources located at the network edge. As noted in the study, edge computing enables placing computing resources closer to the display devices (such as MR devices), at the edge of the network. This feature enables applications that are too resource-intensive to be run closer to the end device and streamed with low latency. Besides computing and graphical rendering resources that enable effective MR experience, engaging interaction with virtual environments is equally significant.

Collaborative interaction methods enable a multiuser interaction with a shared and synchronised virtual and/or real-virtual environment. As a result, this interaction method can easily establish a contextual relationship between users and cultural context by adding a social dimension to the experience. In this regard, a study by Šašinka and Stachoň [25] indicates the importance of adding a social dimension to the knowledge acquisition process in collaborative and interactive visualisation environments. Multi-modal interaction methods integrate multiple modes of interaction, such as speech, gaze, gesture, touch, and movement. This interaction method resembles how we interact with our physical environment and enables users to establish a contextual relationship and collaboratively interact with the real virtual environment. As a result, enhanced engagement with virtual environments and cultural context can be realised due to the method's ease of use and resemblance to natural interaction modalities.

3. System Architecture and Components of the Clouds-Based Collaborative and Multi-Modal MR

This work is a continuation of a previous design and implementation of a "Walkable MR Map" that employed a map-based interaction method to enable engagement and contextual relationship in VH applications [26]. The Walkable MR Map is an interaction method designed and built to use interactive, immersive, and walkable maps as interaction interfaces in a MR environment that allows users to interact with cultural content, 3D models, and different multimedia content at museums and heritage sites. The clouds-based collaborative and multi-modal MR application utilises this map-based approach as a base interaction method and extends the interactivity aspect with a collaborative and multi-modal characteristic. The resulting virtual environment allows a multiuser interaction.

The proposed application has five major components: MR device, Collaborative and Multi-modal Interaction Framework (CMIF), Walkable MR Map Framework, Cultural and Multimedia Content Manager (CMCM), and Shared Location and Session Manager (SLSM). Figure 1 shows the overall system architecture and its major components. A detailed discussion on the architecture is provided below. The discussion will focus mainly on the components that are newly added to the "Walkable MR Map" framework. However, a brief introduction to some components of this existing framework will be provided, when possible, to make the reading smooth.

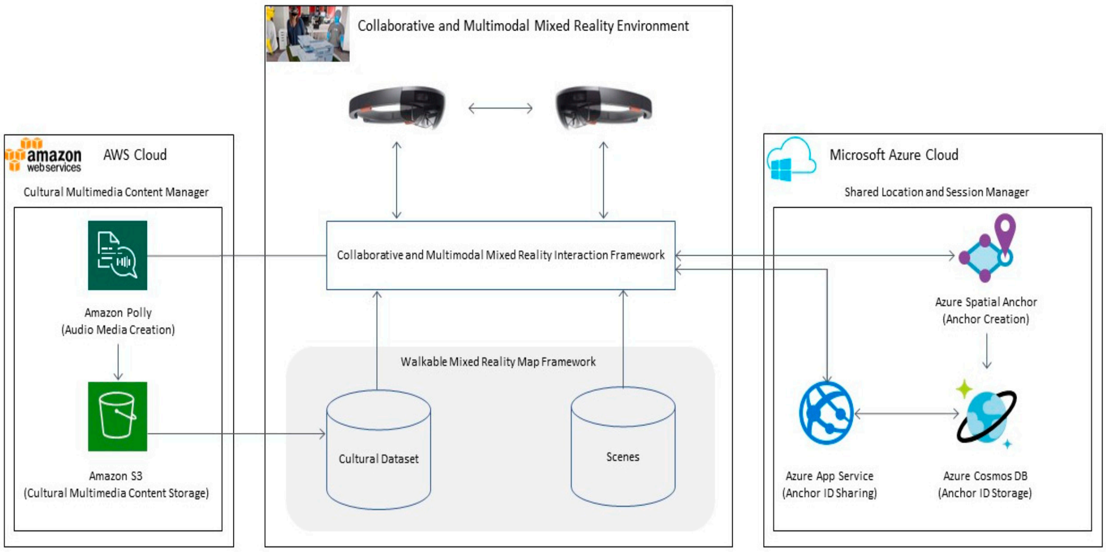


Figure 1. System architecture of the clouds-based collaborative and multi-modal mixed reality (MR).

3.1. MR Devices (Microsoft HoloLens)

The proposed architecture uses a minimum of two Microsoft HoloLens devices to enable collaborative and multi-modal interaction with a shared real-virtual environment.

HoloLens is preferred over other immersive reality devices available in the market because it has inbuilt processing units, tracking, interaction (gaze, gesture, and speech), and rendering capabilities. It also can be integrated with Microsoft Azure Mixed Reality Services[1], such as Azure Spatial Anchors. These features are the enablers of the collaborative and multi-modal aspects of the proposed framework. A detailed discussion of the technical specifications of HoloLens and a complete workflow of application development and deployment are presented in [26,27].

3.2. Collaborative and Multi-Modal Interaction Framework (CMIF)

This component is central to the overall objective of the framework. It builds upon and extends the map-based interaction in the "Walkable MxR Map" architecture. In addition to the interactivity provided, this component introduces collaborative and multi-modal interaction to the experience. To this end, the component integrates with other parts of the framework, namely, SLSM and CMCM.

3.3. Walkable MxR Map Framework

The Walkable MxR Map has five major components: Head-Mounted Display, Geospatial Information and Event Cue, Interaction Inputs and MR (MxR) Framework, Event and Spatial Query Handler, and Cultural Dataset containing historical and cultural context (3D models, multimedia content and event spatiotemporal information). Figure 2 shows the overall system architecture and its major components. A detailed discussion on the overall architecture and on each component is presented in [26].

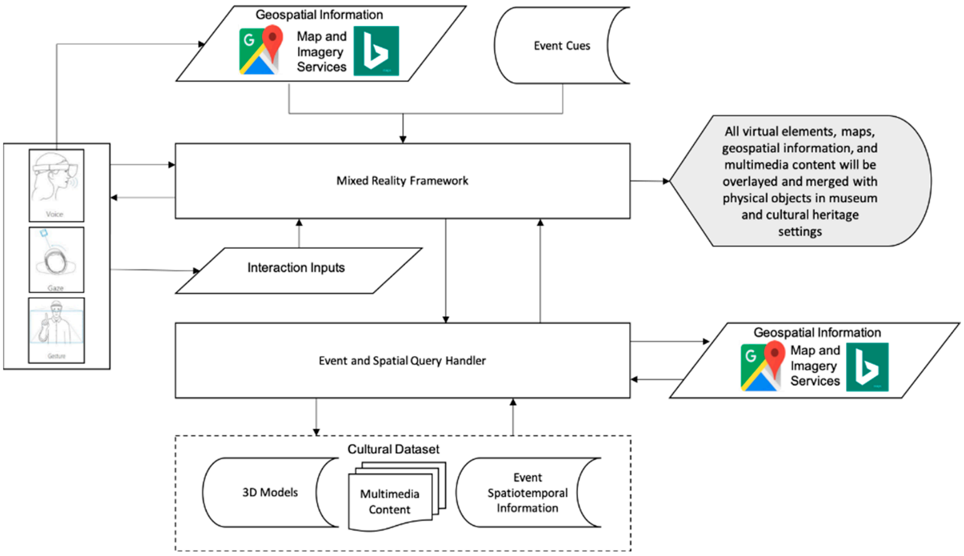


Figure 2. System architecture of the Walkable MR Map [26].

3.4. Cultural Multimedia Content Manager (CMCM)

Cultural Multimedia Content Manager (CMCM) is responsible for the creation, storage, and dissemination of all cultural multimedia content, such as audio and video content. It has two subcomponents, namely, Audio Media Creation (AMC) and Cultural Multimedia Content Storage (CMCS). This component plays a significant role in terms of reducing the MR application size that will be deployed to the HoloLens devices. The deployable application size often gets bigger given that the device is untethered, and developers tend to utilise the storage, processing and rendering capability onboard of the device. As such, their performance will be impacted as the deployed applications need to load all content at run time. The architecture proposed in this paper uses the CMCM to move the storage of such content into cloud-based storage and load specific content at run time to the application using API calls. Hence, the deployable application size can be reduced greatly and allow for more multimedia content sharing as the application will not be limited to the storage size onboard the device. This provides opportunity and flexibility to the application in terms of sharing a wider range of content.

The CMCM relies mainly on two cloud services from Amazon Web Services—Amazon Polly and Amazon S3. Amazon Polly[2] is a cloud service that turns text into lifelike speech. Amazon Simple Storage Service[3] (Amazon S3) is an object storage service that offers scalability, data availability, security, and performance. This cloud storage is used to store content generated by the AMC subcomponent and other multimedia content from external sources. In addition, these cloud services are utilised for two main purposes. First, Amazon Polly is used to generate audio files that enable the proposed framework to include speech-enabled interaction with content and the MR environment. This is achieved by converting textual information sourced from different historical collections and instructions into lifelike speech using Amazon Polly. The converted audio media files are then stored in Amazon S3 and made available for the CMCM to load to a scene at run time. As a result, users are guided through the MR experience by speech-enabled instructions and interactive content. Second, Amazon Polly is also used to generate audio media files in a form of narration about specific cultural contexts presented through the application. The multi-modal aspect of the interaction method relies on this feature.

3.5. Shared Location and Session Manager (SLSM)

This is a crucial component to enable sharing the MR environment across multiple devices, thereby achieving a collaborative experience. To this end, the SLSM component relies on Azure Spatial Anchors[4], Azure Cosmos DB[5], and Azure App Service[6].

Azure Spatial Anchors is a cross-platform service that allows developers to create multi-user and shared experiences using objects that persist their location across devices over time. For example, two people can start a MR application by placing the virtual content on a table. Then, by pointing their device at the table, they can view and interact with the virtual content together. Spatial Anchors can also connect to create spatial relationships between them. For example, a VH application used in museums as a virtual tour guide or wayfinding assistant may include an experience that has two or more points of interest that a user must interact with to complete a predefined visit route in the museum. Those points of interest can be stored and shared across sessions and devices. Later, when the user is completing the visiting experience, the application can retrieve anchors that are nearby the current one to direct the user towards the next visiting experience at the museum.

In addition, Spatial Anchors can enable persisting virtual content in the real world. For instance, museum curators can place virtual maps on the floor or wall, that people can see through a smartphone application or a HoloLens device to find their way around the museum. Hence, in a museum or cultural heritage setting, users could receive contextual information about heritage assets by pointing a supported device camera at the Spatial Anchors.

Azure Cosmos DB is a fully managed, scalable, and highly responsive NoSQL database for application development. The SLSM component uses Azure Cosmos DB as persistent storage for Spatial Anchors identifiers. This service is selected because it is easy to integrate with other Microsoft Azure cloud services. The stored identifiers are then accessed and shared across sessions via Azure App Service. Azure App Service is an HTTP-based service for hosting web applications, REST APIs, and mobile back ends.

4. Implementation of "Clouds-Based Collaborative and Multi-Modal MR"

The system architecture proposed above was implemented using commercial Head-mounted-display (HMD), proprietary software, cloud services, opensource development toolkits, and custom scripts.

4.1. Head-Mounted-Display–Microsft HoloLens

Microsoft HoloLens is a self-contained immersive reality device that runs on Windows MR operating system. The main features of immersive reality devices, including Microsoft HoloLens, can be categorised into four enabler groups: tracking, experience scale, interaction, and spatial awareness [26]. This device has all the features required for tracking, computation, and presenting virtual objects and audio-visual elements. Most HMDs that are currently available in the market, however, rely on high-end VR-ready computers for computation, meaning they always must be physically attached to computing resources or at least connect wirelessly. HoloLens, however, performs all computations using the processing units (CPU and GPU) onboard the device. This extends the applicability of the application to indoor and outdoor settings.

4.2. Cloud Services

As discussed in the previous section, there are five cloud services that have been utilised to build the prototype. A brief introduction to these could services and their overall role in the proposed application has been provided in Section 3. The discussion below focuses on specific features of these services used during the implementation (prototype) stage. Here, it is worth noting that the proposed application can be reproduced using services and platforms from any provider if the technical requirements discussed are met.

1. Amazon Polly is mainly used to convert textual content to lifelike speech. For instance, the built prototype has a scene that introduces the MR device (HoloLens) and interaction methods. This introductory scene informs on how to interact with virtual content and the device using gaze and gestures, such as Air tap and Bloom gestures[7].
2. Amazon S3 is used to store all types of media files the application requires. The files are then retrieved and loaded to the HoloLens device at runtime.
3. Azure Spatial Anchors is primarily used to enable sharing the MR experience across HoloLens devices. The sharing can potentially extend to a range of smartphone devices. The prototype presented in this article, however, targets HoloLens devices.
4. Azure Cosmos DB is used to store Azure Spatial Anchors identifiers for persistent sharing. This service was selected given that it can easily integrate with Azure App Service. Alternatively, any other database, such as Amazon DynamoDB[8], can be used to store the identifiers generated by Azure Spatial Anchors.
5. Azure App Service is used as a web application to post and retrieve anchor identifiers from Azure Cosmos DB.

4.3. Development Platform and Toolkits

The proposed system was prototyped using Unity 2019.4.x, Mixed Reality Toolkit 2.5, Azure Spatial Anchors SDK 2.7, and Microsoft Visual Studio 2019. The Unity game engine was selected because it enables multiplatform game development and deployment. Currently, Unity supports more than 25 platforms. Mixed Reality Toolkit (MRTK) is a Microsoft-driven open source and extensible framework that provides a set of foundational components and features to accelerate MR developments in Unity. The version of MRTK used in this implementation supports a wide range of platforms, such as Microsoft HoloLens 1 and HoloLens 2, Microsoft Immersive Headsets, Windows Mixed Reality Headsets, and OpenVR headsets (HTC Vive/Oculus Rift). Thanks to this toolkit, rapid prototyping via in-editor simulation that allows seeing changes immediately, was achieved. Once the development was ready to deploy onto target devices. Microsoft Visual Studio 2019 was used for debugging and deploying the code from Unity to HoloLens.

5. Discussion

The implementation of the clouds-based MR architecture proposed above was realised using the tools, technologies and cloud services discussed in the previous sections. This section will provide a detailed discussion on the built prototype, experiential aspects of the application, limitations and areas identified for future improvement. It also provides a brief historical context of SS Xantho[9], the heritage asset used as a case study for the prototype.

5.1. The Story of SS Xantho: Western Australia's First Coastal Steamer (1848–1872)

Note: the following text is extracted and compiled from materials published by Western Australia Museum [28–30].

The paddle steamer Xantho, one of the world's first iron ships, was built in 1848 by Denny's of Dumbarton in Scotland. Like most 19th century steamships, Xantho was driven by both sails and steam. In 1871, after 23 years of Scottish coastal service, Xantho was sold to Robert Stewart, 'Metal Merchant' (scrap metal dealer) of Glasgow. Rather than cut it up for scrap, he removed the old paddlewheel machinery and replaced it with a ten-year-old propeller engine built by the famous naval engineers, John Penn and Sons of Greenwich. Stewart then offered the 'hybrid' ship for sale.

Xantho's new owner was the colonial entrepreneur Charles Edward Broadhurst, who visited Glasgow partly to purchase a steamer to navigate Australia's northwest. In November 1872 on her way south from the pearling grounds, Xantho called in to Port Gregory, and there, ignoring his captain's pleas, Broadhurst overloaded his ship with a cargo of lead ore. On the way south to Geraldton the worn-out SS Xantho began to sink. Soon after entering Port Gregory, they hit a sandbank and the water already in the ship tore through three supposedly watertight bulkheads, entered the engine room, and doused the boiler fires. This rendered the pumps inoperable, and the ship slowly sank, coming to rest in 5 metres of water, about 100 metres offshore.

In 1979, when searching for the Xantho for Graeme Henderson, the Western Australia Museum's head of the colonial wreck program who was researching the very late transition from sail to steam on the Western Australia coast, volunteer divers from the Maritime Archaeological Association of Western Australia (MAAWA) were led to what they knew as the 'boiler wreck' by Port Gregory identities Robin Cripps and Greg Horseman. A wreck report from the MAAWA team was filed, together with artist Ian Warne's impressions showing how the wreck had disintegrated over the years. Figure 3 presents impressions showing how the wreck of SS Xantho disintegrated.

In 1983, following reports of looting at the site, the task of examining and protecting the site was given to the Museum's Inspector of Wrecks, M. (Mack) McCarthy, who has coordinated all aspects of the project ever since.

5.2. Interacting with the Clouds-Based Collaborative and Multi-Modal MR Application

The prototype built as part of the clouds-based MR application has two different flavours or versions—Xantho-Curator and Xantho-Visitor (See Table 1). The features and modes of interaction are slightly different between these two versions of the prototype.

Table 1. Features of Xantho-Curator and Xantho-Visitor versions of the clouds-based MR application.

Feature	Xantho-Curator	Xantho-Visitor
Create Spatial Anchor object (Stage ID)	Xantho-Curator can create, store, and retrieve Spatial Anchor objects and their identifiers	Xantho-Visitor cannot create Spatial Anchor objects
Locate Spatial Anchor object (Stage ID)	Xantho-Curator can locate previously created and stored Spatial Anchor objects	Same as Xantho-Curator
Modes of interaction	Xantho-Curator can use gaze, gesture, and speech to interact with the virtual environment	Same as Xantho-Curator
Introductory Scene	The assumption is that Xantho-Curator users are not new to the HoloLens device. Hence, this version does not include an introductory scene.	Xantho-Visitor loads the introductory scene (focusing on modes of interaction) when the experience begins. This is assuming users are new to the HoloLens device.

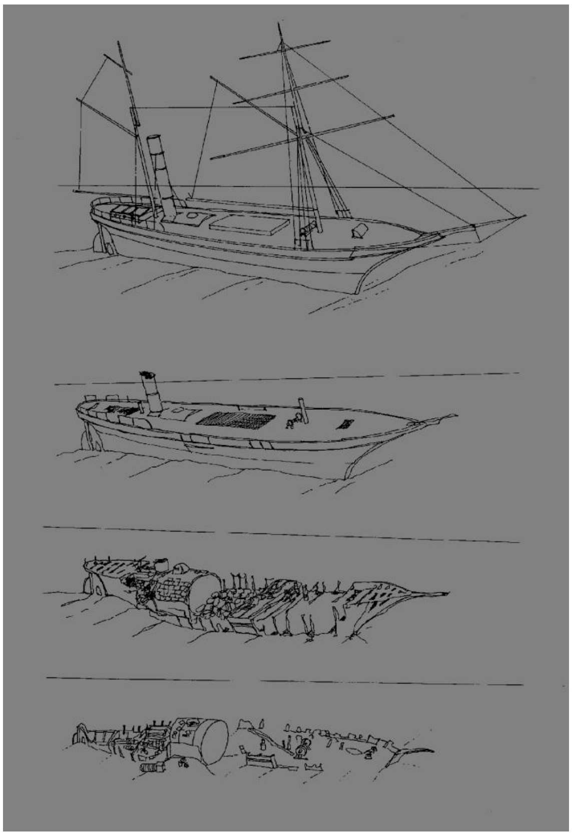


Figure 3. Artist Ian Warne's impressions showing how the wreck of SS Xantho disintegrated. Image courtesy (Ian Warne, MAAWA).

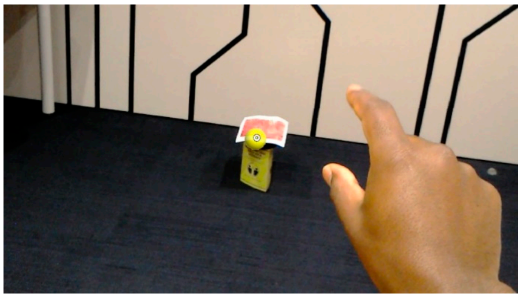
Both Xantho-Curator and Xantho-Visitor allow users to interact with the display device (HoloLens) via a combination of gaze, gesture, and speech. In terms of functionality, Xantho-Curator provides a unique feature to create Spatial Anchor objects that will serve as a stage for the collaborative MR environment.

Interaction with the collaborative MR environment always begins with the Xantho-Curator version user either retrieving or creating the Spatial Anchor object that servers as a shared stage for the experience. Once a stage is identified (Spatial Anchor object created and/or located), an identical MR environment will be loaded to the HoloLens device for both users (Xantho-Curator and Xantho-visitor) to interact with. This plays a significant role to augment users' interactive experience with a sense of collaboration and engagement. Figures 4 and 5 show each step of Xantho-Curator and Xantho-Visitor, respectively. Interested readers can visit the link provided under Supplemental Materials section to access video file that shows how the built prototype functions.

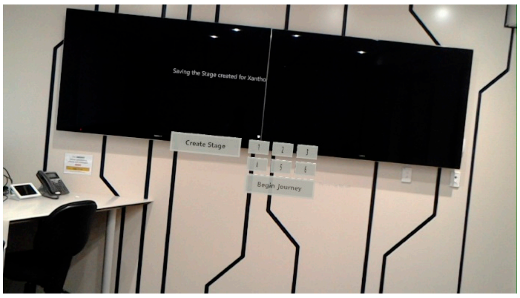
5.3. Expected Impact of the Clouds-Based MR Application on Cultural Learning

The key theoretical background that led to designing and building a clouds-based collaborative and multi-modal MR application is the assumption that contextual relationship and engagement lead to enhanced cultural learning in VH environments. It is further assumed that VH environments can be augmented with these properties via a combination of immersive reality technology and collaborative and multi-modal interaction methods.

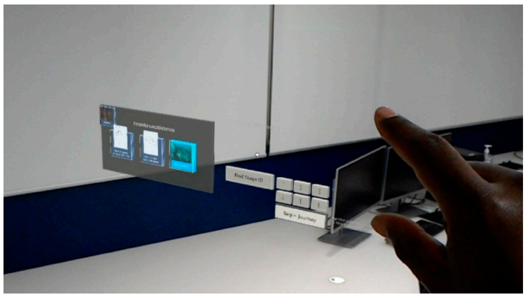
(**a**) Xantho-Curator version asks the user to air tap on the picture of SS Xantho placed on the floor. This location will be used as a stage to load the MxR environment.



(**b**) User performs an air tap on the picture of Xantho and the application creates a Spatial Anchor object.



(**c**) The Spatial Anchor object created in the previous step is stored in the cloud and its identifier is displayed to the user. This identifier is then used as a Stage ID for the MR experience.



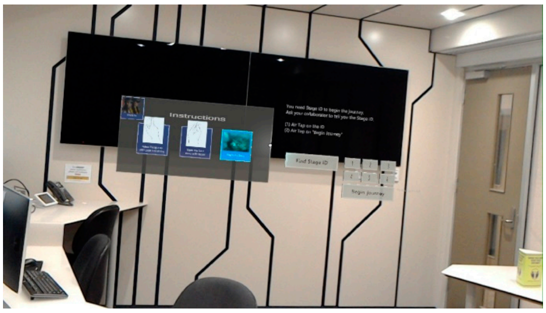
(**d**) The user shares the Stage ID with their collaborator and begins the MR experience, which will take place at the exact location where a Spatial Anchor object is created.

Figure 4. User interacting with the Xantho-Curator version of the clouds-based MR application. (**a**) user is asked to air tap on the picture of Xantho placed on the floor; (**b**) Spatial Anchor object is created and stored into the cloud Azure Spatial Anchor Service; (**c**) the application will display the identifier of the stored Spatial Anchor object, and; (**d**) user shares the identifier to their collaborator (user interacting with the Xantho-Visitor version) and begins the shared and collaborative MR experience together with their collaborator.

The clouds-based MR application is, therefore, expected to provide a shared real-virtual space that enhances cultural learning and enriches users' experience by (1) establishing a contextual relationship and engagement between users, virtual environments and cultural context in museums and heritage sites, and (2) by enabling collaboration between users.

5.4. Applicabilty of the Clouds-Based Mixed Realtiy—Museums and Heritage Sites

Conventional museums and heritage sites are known for preventing physical manipulation of artefacts. Visitors acquire knowledge about the artefacts from curators, guides, printed media and digital multimedia content available in museums and heritage sites. The clouds-based MR application, however, enables users to collaboratively manipulate and interact with the digital representations of the artefacts (3D models) via an interactive and immersive virtual environment, thereby resulting in a real virtual space where visiting experience can be augmented with a social and virtual presence. This enhances the learning experience since the cultural context presented to users is dynamic and interactive, rather than a linear information presentation format pre-determined by curators and cultural heritage professionals. The application can also be used to enable collaborative experience between curators located in museums and remote visitors/users wandering at heritage sites or vice versa. Curators in the museum can communicate and collaborate with remote visitors to provide guidance.

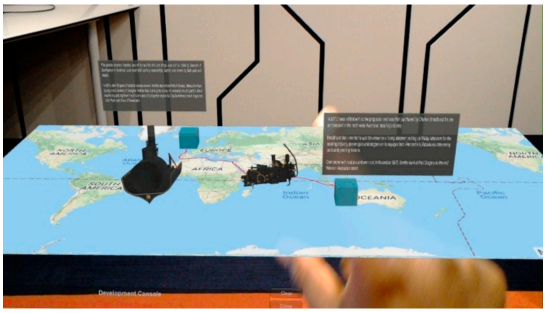


(**a**) Xantho-Visitor version asks the user to obtain a Stage ID from their collaborator who interacts with the Xantho-Curator version to set up the Stage ID.

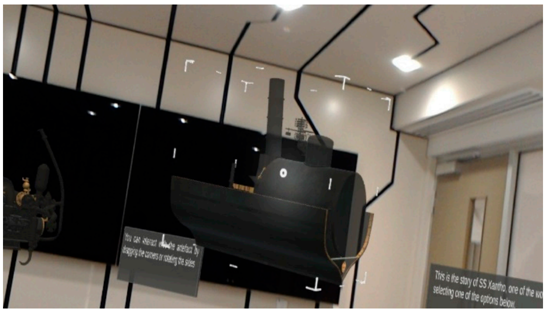
(**b**) Once the Spatial Anchor object is located for the Stage ID provided, the Xantho-Visitor loads the relevant scene. At this stage, both users of Xantho-Curator and Xantho-Visitor start interacting with the identical virtual environment.

(**c**) User can interact with specific virtual objects and content.

(**d**) More content will be loaded to the scene as the user progresses through the MR experience



(**e**) User can interact with 3D models at different scales.



(**f**) User can manipulate and rotate 3D models.

Figure 5. User interacting with the Xantho-Visitor version of the clouds-based MR application. (**a**) user is asked to provide stage ID, a Spatial Anchor identifier they received from their collaborator; (**b**–**d**) the MR application will locate the shared Spatial Anchor object and loads the relevant scene at the exact location that was stored by the Xantho-Curator version, and; (**e**,**f**) both the Xantho-Curator and Xantho-Visitor version user of the application will interact with the MR environment displayed at a location identical to both users.

6. Conclusions

In this paper, we have presented a clouds-based collaborative and multi-modal MR application designed and built for VH. The primary objective of the application is enhancing cultural learning through engagement, a contextual relationship, and an interactive virtual environment. The implementation of the proposed application has utilised cloud services, such as Amazon Polly, Amazon S3, Azure Spatial Anchors, Azure Cosmos DB, and Azure App Service. In addition to cloud services, the implementation phase has exploited immersive reality technology (specifically, Microsoft HoloLens) and development tools and platforms, such as Unity, Mixed Reality Toolkit, Azure Spatial Anchors SDK, and Microsoft Visual Studio. SS Xantho, one of the world's first iron ships and Western Australia's first coastal steamer, was used as a case study for the prototype. Future works will attempt to evaluate the clouds-based MR application with curators, VH and cultural heritage professionals to validate whether the application enhances cultural learning in VH applications.

Supplementary Materials: Interested readers can visit the link provided to access video file that shows how the built prototype functions. https://cultural-dataset.s3.ap-southeast-2.amazonaws.com/xantho/video/XanthoMR.mp4.

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Conflicts of Interest: The author declares no conflict of interest.

Notes

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Chapter 8

The Influence of Collaborative and Multi-Modal Mixed Reality: Cultural Learning in Virtual Heritage

Publication review:

1. Evaluates the clouds-based collaborative and multi-modal mixed reality in the context of cultural learning in virtual heritage.

2. Based on the outcome of the evaluation, it also provides some suggestions to the wider virtual heritage community on the topics of mixed reality, interaction methods and cultural learning.

Multimodal Technologies and Interaction

Article

The Influence of Collaborative and Multi-Modal Mixed Reality: Cultural Learning in Virtual Heritage

Mafkereseb Kassahun Bekele [1,*], Erik Champion [1,2,3,4], David A. McMeekin [5,6] and Hafizur Rahaman [1]

1 School of Media, Creative Arts and Social Inquiry (MCASI), Curtin University, Perth, WA 6102, Australia; erik.champion@uwa.edu.au (E.C.); hafizur.rahaman@curtin.edu.au (H.R.)
2 Centre for Digital Humanities Research, Australian National University, Sir Roland Wilson Building, 120 McCoy Circuit, Canberra, ACT 2601, Australia
3 School of Social Sciences, University of Western Australia, 35 Stirling Highway, Perth, WA 6907, Australia
4 City West Campus, University of South Australia, P.O. Box 2471, Adelaide, SA 5001, Australia
5 School of Earth and Planetary Sciences, Curtin University, Perth, WA 6845, Australia; david.mcmeekin@curtin.edu.au
6 School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, WA 6845, Australia
* Correspondence: mafkereseb.bekele@postgrad.curtin.edu.au

Abstract: Studies in the virtual heritage (VH) domain identify collaboration (social interaction), engagement, and a contextual relationship as key elements of interaction design that influence users' experience and cultural learning in VH applications. The purpose of this study is to validate whether collaboration (social interaction), engaging experience, and a contextual relationship enhance cultural learning in a collaborative and multi-modal mixed reality (MR) heritage environment. To this end, we have designed and implemented a cloud-based collaborative and multi-modal MR application aiming at enhancing user experience and cultural learning in museums. A conceptual model was proposed based on collaboration, engagement, and relationship in the context of MR experience. The MR application was then evaluated at the Western Australian Shipwrecks Museum by experts, archaeologists, and curators from the gallery and the Western Australian Museum. Questionnaire, semi-structured interview, and observation were used to collect data. The results suggest that integrating collaborative and multi-modal interaction methods with MR technology facilitates enhanced cultural learning in VH.

Keywords: mixed reality; virtual heritage; collaborative interaction; multi-modal interaction; engagement; cultural learning

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1. Introduction

The adoption of immersive reality technologies across different domains and application themes, such as architecture, medical practice, engineering, and tourism, has increased recently [1–8]. For instance, Alizadehsalehi, Hadavi [1] review the existing literature, case studies, and applications of immersive reality technology in Architecture, Engineering, and Construction (AEC) industry and outline a roadmap that promotes the integration of immersive reality technology, cloud computing, digital twins, emerging technologies in IoT and cognitive computing to solve a variety of construction and management issues in the industry. Similarly, Alizadehsalehi and Yitmen [2] present a framework that integrate digital twin, building information modelling (BIM), and immersive reality technology, aiming at monitoring construction progress.

The tourism industry, digital cultural heritage, and architectural heritage have benefited from immersive reality. In recent years, studies applied to these domains have demonstrated how the integration of cultural computing, 3D modelling, and immersive reality improve awareness of cultural heritage [4]. Furthermore, studies also show how immersive reality plays a role in reviving the tourism industry from its COVID-19 pandemic-induced economic challenges [5].

Recent studies in the virtual heritage (VH) domain have recognised the importance of collaboration, social interaction, and engagement in exhibiting technologies that museums provide to visitors [9,10]. In this regard, immersive reality technologies are becoming a popular choice to enhance visitors' experience.

Museums are shared spaces, and it is very crucial that immersive reality technologies embrace this characteristic. However, not all forms of immersive reality technologies can naturally enable collaboration between visitors. For instance, virtual reality (VR) creates an artificial barrier between visitors and between the real and virtual words. In contrast, Augmented Reality (AR) and Mixed Reality (MR) do not create artificial barrier between visitors because virtual objects are overlayed on top of visitors' views of the real world. Hence, social interaction between visitors and a contextual relationship between visitors and the real world can be maintained.

In this paper, we evaluate a mixed reality application designed and implemented to enhance cultural learning in museums. The mixed reality application (Clouds-based Collaborative and Multi-modal Mixed Reality) attempts to enable collaboration, engagement, and a contextual relationship in mixed reality applications that specifically aim at virtual heritage themes in the context of enhancing cultural learning.

This paper is a continuation of previous published works produced as part of the first author's PhD research project. The publications are summarised and presented in Table 1 to make the reading smoother and establish a connection between the papers. The published works are categorized into four research phases.

Phase one: Exploring the state-of-the-art

- A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage [11].
- A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage [12].

Phase two: Establishing the conceptual base

- Redefining Mixed Reality: User-Reality-Virtuality and Virtual Heritage Perspectives [13].
- Mixed Reality: A Bridge or a Fusion Between Two Worlds? [14].

Phase three: Design and implementation

- From Photo to 3D to Mixed Reality: A Complete Workflow for Cultural Heritage Visualisation and Experience [15].
- Walkable Mixed Reality Map as Interaction Interface for Virtual Heritage [16].
- Clouds-Based Collaborative and Multi-Modal Mixed Reality for Virtual Heritage [17].

Phase four: Evaluation

- The Influence of Collaborative and Multi-modal Mixed Reality: Cultural Learning in Virtual Heritage (this paper).

The remainder of this paper is structured as follows. Section 2 will discuss existing studies in the context of providing theoretical background for the study. Section 3 will provide detailed discussion on the research model and explores various assumptions. Following that, Section 4 will explain the research methodology adopted. Section 5 will present detailed discussion on data analysis and results. Finally, Sections 6 and 7 will offer discussions and conclusions, including theoretical contribution, practical benefits to the virtual heritage domain, and future works.

Table 1. Summary of previous publications that led to this this study.

Research Phases and Published Works
1. A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage [11] Publication review • Provides a comprehensive review of immersive reality technologies from cultural heritage perspective. • Reveals areas of research concentration and deficiency in the field. • Highlights limitations of existing technologies and impediments to future research. • Provides a framework for comparing state-of-the-art systems (immersive reality) and understanding which solutions are most appropriate for a given virtual heritage application. 2. A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage [12] Publication review • Identifies common interaction methods employed in virtual heritage. • Discusses immersive reality technologies in the context of cultural learning and virtual heritage. • Based on existing literature, this study establishes collaboration, engagement, and a contextual relationship as experiential factors that enable cultural learning in virtual heritage. • Compares various interaction methods and immersive reality technologies against their potential to enable collaboration, engagement, and a contextual relationship. • Following the comparison, this study identifies hybrid interaction method (collaborative and multi-modal) and mixed reality as a suitable combination to enable cultural learning in virtual heritage.
3. Redefining Mixed Reality: User-Reality-Virtuality and Virtual Heritage Perspectives [13] Publication review • Identifies the gap in existing definition of mixed reality from virtual heritage perspective. • Identifies a contextual relationship, which is one of the three factors to enable cultural learning in virtual heritage, as a fundamental component to redefine mixed reality. • Presents a redefinition of mixed reality from a perspective emphasising the contextual relationship between users, reality, and virtuality. 4. Mixed Reality: A Bridge or a Fusion Between Two Worlds? [14] Publication review • Based on the redefinition of mixed reality presented in the published work above, this study further explores mixed reality from virtual heritage perspective. • Attempts to review the common depictions of mixed reality in existing body of literature in the context of different application themes in virtual heritage. • Establishes a boundary between augmented reality and mixed reality. • Conveys the view that mixed reality is more a fusion of the real and virtual environment rather than a bridge between these worlds or a combination of properties of augmented and virtual reality. • Identifies application themes and limitations of mixed reality in the context of virtual heritage.
5. From Photo to 3D to Mixed Reality: A Complete Workflow for Cultural Heritage Visualisation and Experience [15] Publication review • Provides, demonstrates, and shows practical implementation of methods to generate 3D models. • Provides workflow for deploying 3D models to Microsoft HoloLens device. 6. Walkable Mixed Reality Map as Interaction Interface for Virtual Heritage [16] Publication • Proposes and implements a novel approach to use immersive maps as interaction interfaces in a mixed reality environment applied to specific virtual heritage setting. 7. Clouds-Based Collaborative and Multi-Modal Mixed Reality for Virtual Heritage [17] Publication review • Extends the "Walkable Mixed Reality Map" to include collaborative and multi-modal interaction methods. • Designs and implements a novel approach that integrates cloud computing, mixed reality, and virtual heritage.
8. The Influence of Collaborative and Multi-Modal Mixed Reality: Cultural Learning in Virtual Heritage (this paper) Publication review: • Evaluates the clouds-based collaborative and multi-modal mixed reality in the context of cultural learning in virtual heritage. • Based on the outcome of the evaluation, it also provides some suggestions to the wider virtual heritage community on the topics of mixed reality, interaction methods, and cultural learning.

2. Theoretical Background

This section provides detailed discussion on different domains and exemplar cases that contributed to forming the primary research objective.

2.1. Mixed Reality and Virtual Heritage

Virtual heritage is an emerging field that applies immersive reality technologies and digital tools to cultural heritage (CH) to simulate, preserve, and disseminate tangible and intangible cultural heritage assets in the form of diverse multimedia approaches. Immersive reality is one of the approaches utilised for various virtual heritage application themes ranging from virtual reconstruction to virtual museum [11,12]. For instance, mixed reality enables user-centred and personalised presentation while allowing cultural heritage assets to be digitally accessible in the form of virtual reconstruction or virtual museums or exhibitions.

Mixed reality applications are emerging in many domains, following recent advances in immersive reality technology, such as the Microsoft HoloLens device. For instance, Pollalis, Minor [18] present a mixed reality application that utilises this device to allow object-based learning through mid-air gestural interaction and virtual representations of museum artefacts. Other examples of HoloLens-based applications in the domain include [15–17,19–22]. Mixed reality applications in virtual heritage that utilise similar technology tend to focus on virtual reconstruction, virtual representation, and virtual exhibition.

Virtual reconstruction and representation aim at enabling users to visualise and interact with digitally reconstructed tangible and intangible heritages. Such applications allow blending historical views from the past with their current appearance. For instance, damaged architectural assets can be virtually reconstructed at their historical location. Additional information beyond the virtual reconstruction itself can also be overlaid along with the virtual elements. MR can play an important role in the restoration of lost heritages, starting from interacting with the virtual reconstruction of statues and extending to reviving cultural practices in their original forms.

Virtual museums and virtual exhibitions intend to improve visitors' experience at museums and heritage sites, typically through personalised and immersive virtual tour guidance. In general, such applications simulate and enhance museums and heritage sites, including their tangible and intangible assets.

2.2. Collaborative and Multi-Modal Interaction Methods

Collaborative interaction methods in immersive reality applications consist of collaboration as a default characteristic. To this effect, the interaction method integrates and synchronises various input and audio-visual display devices [23]. The objective of the collaborative interaction method is to facilitate interaction with virtual environment that enables shared and multiuser experience. Similarly, multi-modal interaction methods consist of multiple modes of interaction, such as speech, gaze, gesture, touch, and movement. The integration of collaborative and multi-modal interaction methods facilitates collaboration between users and provides natural interaction. Furthermore, this interaction method with mixed reality adds a face-to-face collaboration to the experience and facilitates interaction among users. Bekele and Champion [12] (pp. 8–12) discuss collaborative and multi-modal interaction methods and how their integration with mixed reality enhances cultural learning in virtual heritage.

2.3. Collaboration, Engagement, Contextual Relationship, and Cultural Learning

Virtual environments can facilitate enhanced cultural learning experience (Ibrahim & Ali, 2018). Interaction methods, contextual relationship, and cultural context in virtual heritage also play an important role in enhancing cultural learning [24–31]. Enhancing cultural learning in VH applications, therefore, relies on immersive reality and interaction method to enable a contextual relationship, collaboration, and engagement between users and the virtual environment [24,32–34]. Existing virtual heritage applications that utilise immersive reality technologies for cultural knowledge dissemination focus on users' interaction with the applications [35–38]. For instance, mixed reality allows interaction between users and the real-virtual world. This allows virtual heritage applications to establish a contextual relationship between users and the real-world. Bekele and Champion [12] (pp. 5–8) and Bekele and Champion [13] (pp. 5–7) discuss how collaborative and multi-modal mixed reality can enhance cultural learning through collaboration, engagement, and a contextual relationship in mixed reality virtual heritage environment.

3. Conceptual Model

In this section, we discuss our conceptual model. Based on the theoretical background presented in the previous section, we discuss the research model (framework) that led to the design, implementation, and evaluation of clouds-based collaborative and multi-modal mixed reality [17]. Figure 1 shows our conceptual model, which presents the characteristics of collaborative and multi-modal mixed reality affecting users' cultural learning experience via collaboration, engagement, a contextual relationship, and their associated enablers. Establishing enhanced cultural learning as our objective, we also outline how the major characteristics of collaborative and multi-modal mixed reality influence cultural learning in virtual heritage applications at museums and heritage sites. We further explore how these characteristics are connected to and influence each other to attain the primary objective.

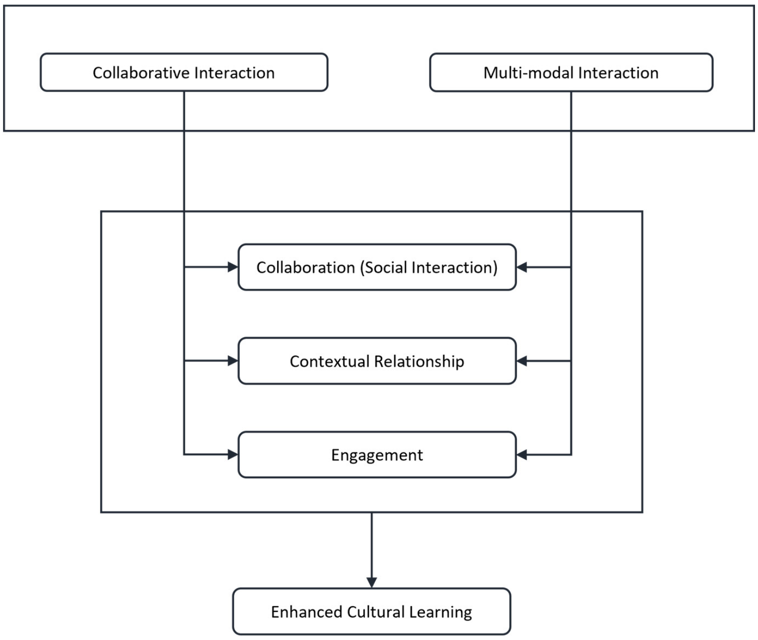


Figure 1. Conceptual model.

3.1. Collaborative Interaction, Collaboration (Social Interaction), Contextual Relationship, and Engagement

Collaborative interaction refers to the ability of interaction methods to enable effective and meaningful collaboration between users. As discussed in the previous section, collaboration, engagement, and contextual relationships influence cultural learning in virtual heritage. When viewed as characteristics of cultural learning in virtual heritage, collaborative interaction, therefore, can enable social interaction, a contextual relationship, and engagement. Hence, we hypothesise that collaborative interaction in mixed reality will have a positive effect on engagement, collaboration (social interaction), and a contextual relationship between users and the virtual environment.

3.2. Multi-Modal Interaction, Collaboration (Social Interaction), Contextual Relationship, and Engagement

Multi-modal interaction methods in mixed reality enable users to manipulate the virtual environment and interact with the application via multiple modes, such as gesture, speech, movement, and gaze. These characteristics lead to more natural way of interaction that requires less effort form users. As a result, users will not be distracted by the complexity of the interaction methods, that in turn results in enhanced engagement that facilitates a real-virtual environment to establish a contextual relationship between users and the environment itself. Hence, we hypothesise that multi-modal interaction in mixed reality will have a positive effect on engagement and the contextual relationship between users and the virtual environment.

3.3. Collaboration (Social Interaction) and Cultural Learning

Collaboration (social interaction) in virtual environments, as discussed in the previous section, is one of the characteristics of collaborative and multi-modal mixed reality. We have discussed in the introductory section that museums are shared spaces. As such, social interaction is often implicit in the visiting experience. However, contextual cultural interaction with artefacts, displays, and related media is seldom effectively leveraged. Interaction methods in virtual heritage applications need to embrace this potential. We hypothesise that collaboration (social interaction) in mixed reality will have a positive effect on cultural learning.

3.4. Contextual Relationship and Cultural Learning

Contextual relationship is a three-way relationship between users, the real world, and the virtual environment [13]. The relationship between the virtual environment and the real world is as crucial as the social interaction between users. We hypothesise that contextual relationship in mixed reality will have a positive effect on cultural leaning.

3.5. Engagement and Cultural Learning

Engagement in virtual environments, as discussed in the previous section, is one of the characteristics of collaborative and multi-modal mixed reality. We hypothesise that engagement in mixed reality will have a positive effect on cultural leaning.

4. Method

4.1. Study Context

Figure 2 shows SS Xantho, launched in 1848, which is one of the world's first iron ships and western Australia's first coastal steamer. Xantho was selected as the cultural context for the collaborative and multi-modal mixed reality application we evaluate in this paper [17,39]. Xantho was selected because of its significance to the maritime archaeology of western Australia (it has also been depicted in Aboriginal rock art), it was used as a "tramp steamer", pearler, and convict ship, before sinking in 1872. Besides a permanent section in the Western Australia Shipwreck Museum, featuring the ship and related artifacts, the museum has made available 3D models of the ship and its engine " . . . the only known example of the first high pressure, high revolution engines ever made." As part of this study, two mixed reality applications, Walkable Mixed Reality Map [14] and Clouds-based Collaborative and Multi-modal Mixed Reality [17] were designed and implemented. Both applications use the story of Xantho as their cultural context.

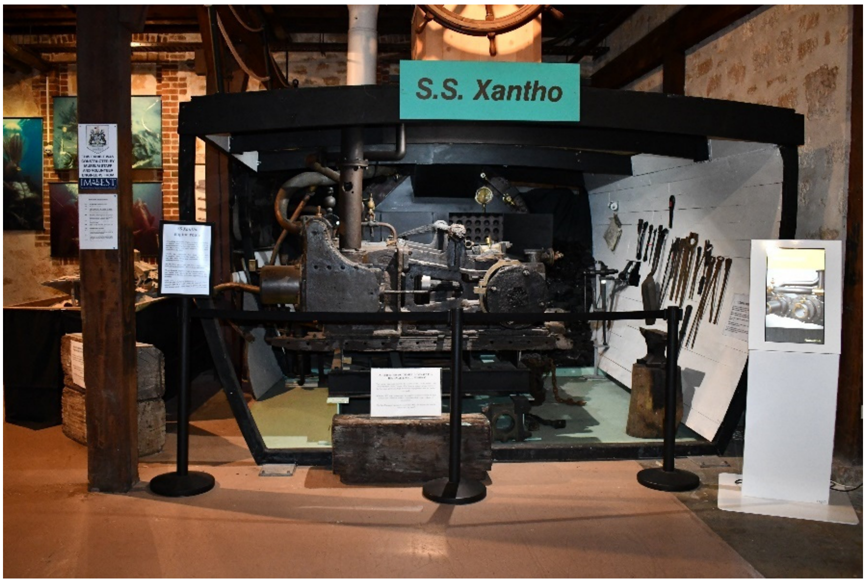
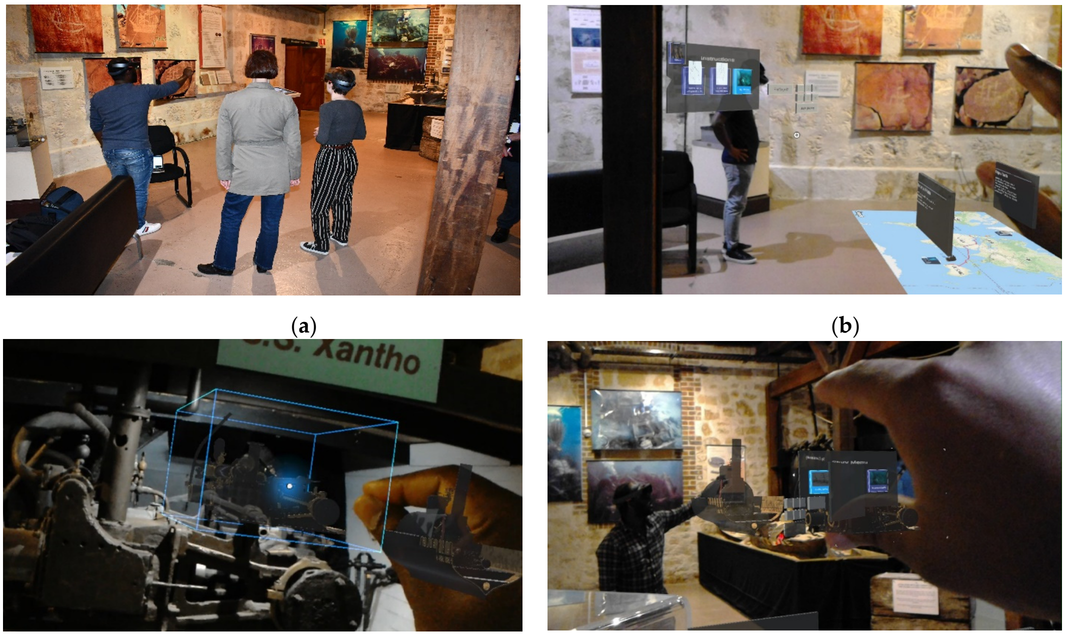


Figure 2. SS Xantho in Western Australia Shipwreck Museum.

The evaluation in this study will focus on the Clouds-Based Collaborative and Multi-Modal Mixed Reality. By using this mixed reality application at the Western Australia Shipwreck Museum, visitors can collaboratively interact with 3D models, videos, audio, and textual information related to Xantho. The experience is delivered to users via Microsoft HoloLens device. A total of two users can collaborate and interact with the mixed reality experience at the same time. Users have a choice of speech, gaze, gesture, and movement to use to interact with the mixed reality environment. They can interact with 3D models, read text, and play audio and video the media content presented. The two users experiencing the mixed reality environment can collaborate and communicate while navigating through the story of Xantho.

The experience begins with the application asking users to provide stage ID to locate a shared location that will be used to load the mixed reality environment onto. Figure 3 shows users interacting with the application (see the Supplemental Materials to view video of the mixed reality experience). The stage ID can be set and passed to users either by a curator or one of the participants who plays a role of a guide [17]. We invite readers to refer to this published article. Once users supply the stage ID, the HoloLens devices will load the mixed reality environment at the shared location and users start interacting with the environment. The experience takes approximately 15–20 min and has four segments. The first segment introduces users to Microsoft HoloLens and the interaction methods they can utilise. The introduction is delivered by a male virtual guide. After this segment, users select to begin the story of Xantho and then the Walkable Mixed Reality Map (second segment) is projected on the floor. At this stage, users start to explore the content collaboratively. This segment focuses on the early life of Xantho. After this stage, users can freely navigate through segment three (focuses on the wreck of Xantho) and segment four (focuses on the discovery of the wreck of Xantho). Interaction with content and the environment is achieved via a multi-modal interaction method that combines speech, gaze, gesture, and movement. This provided users with the flexibility of switching between different modes.



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

Figure 3. Users interacting with the clouds-based collaborative and multi-modal mixed reality application. (**a**) A total of two users interact with the collaborative and multi-modal mixed reality application at Western Australia Shipwreck Museum. (**b**) A total of two users collaboratively interact and explore the Walkable Mixed Reality Map. (**c**) User interacting with 3D model. (**d**) A total of two users interacting with 3D models.

4.2. Measures

The instruments used for the evaluation were questionnaires and semi-structured interviews. The questionnaire used for this study had a total of nine measurement items scored on a 5-point Likert scale, one open question, and six demography questions (see Tables 2 and 3). The measurement methods were adopted from Technology Acceptance Model (TAM) and Bae, Jung [40]. The semi-structured interview had five predetermined questions.

4.3. Data Collection

The survey and interview were conducted over two evaluation sessions that took place at the Western Australian Shipwreck Museum on the 7 and 14 October 2021. The evaluation was conducted by the primary author as part of his PhD research. Experts, archaeologists, curators, and researchers from the museum participated in the evaluation.

After completing the mixed reality experience, participants were given a tablet computer to respond to the questionnaire. Once responses were gathered, participants were asked five semi-structured questions. The interview was recoded on a recording device (smartphone) and transcribed for further analysis.

A total of 11 experts from different departments of the Western Australian Shipwreck Museum participated in the evaluation. Table 2 shows demographical details of the participants. According to the data gathered from the two evaluation sessions, the majority of participants were female (6 female, 4 male, and 1 preferred not to identify gender). The majority of participants were aged between 40 and 49. With regards to participants' previous experience with immersive reality technology in general, the responses show that 7 participants were novice users, and 3 participants had never used the technology (one participant did not respond to this survey item). However, participants' response to a survey item that asked their previous experience with Microsoft HoloLens showed that the majority of participants were new to the technology (8 never used the technology, and 3 were novice users).

Table 2. Demographic characteristics of participants (n = 11).

	Category	Frequency (Count)
Gender	Male	4
	Female	6
	Prefer not to say	1
Age	20 s	1
	30 s	1
	40 s	5
	50 s	2
	60 s	2
Academic Background	Trade/technical/vocational training	1
	Associate degree	0
	Bachelor's degree	6
	Master's degree	2
	Doctorate degree	2
Relationship with Western Australia Shipwreck Museum	Current employee	9
	Past employee	0
	Guest professional/researcher	2
Previous experience with augmented, virtual, and mixed reality	Never used this technology	3
	Novice user	7
	Expert user	0
Previous experience with Microsoft HoloLens	Never used Microsoft HoloLens	8
	Novice user	3
	Expert user	0

Table 3. This table shows participants (n = 11) response to survey items scored on 5-scale Likert (strongly disagree = 1, somewhat disagree = 2, neither agree nor disagree = 3, somewhat agree = 4, and strongly agree = 5), open question presented to participants, and predefined interview questions.

#	Question	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree	Total
Q1	It was easy for me to collaborate with the person I shared the mixed reality experience with.	0	0	2	2	7	11
Q2	It was easy for me to share and explain what I was seeing.	0	0	0	4	7	11
Q3	I enjoyed this shared mixed reality experience.	0	0	1	0	9	10

Table 3. *Cont.*

#	Question	Strongly Disagree	Somewhat Disagree	Neither Agree nor Disagree	Somewhat Agree	Strongly Agree	Total
Q4	It was easy for me to relate the virtual experience with physical items in the gallery.	0	1	0	3	7	11
Q5	It was easy for me to use speech command to interact with the system.	0	0	1	7	3	11
Q6	It was easy for me to use gesture command to interact with the system.	0	0	2	5	4	11
Q7	I think the experience can enhance visitors' interest to explore more collections in the museum.	0	0	0	2	9	11
Q8	I think visitors will find the system easy to use and follow.	0	3	2	5	1	11
Q9	I would like to see more items from the gallery presented in the system.	0	0	3	1	7	11
Open and Interview Questions		Do you think this technology can be used to enhance visitors' interest in the museum's collections?					
		Were the two of you able to communicate while exploring the shared mixed reality experience?					
		Were you able to interact with the system using all modes of interaction, such as gaze, speech, and gesture?					
		Do you have any other thoughts or comments about your experience?					

5. Results

In this section we present the results obtained from analysing the data gathered from survey items, open question, and semi-structured interview. Table 3 and Figure 4 summarise questionnaire items scored on a 5-point Likert scale. The results are grouped into three categories based on the three characteristic of collaborative and multi-modal mixed reality we identified in Sections 2 and 3.

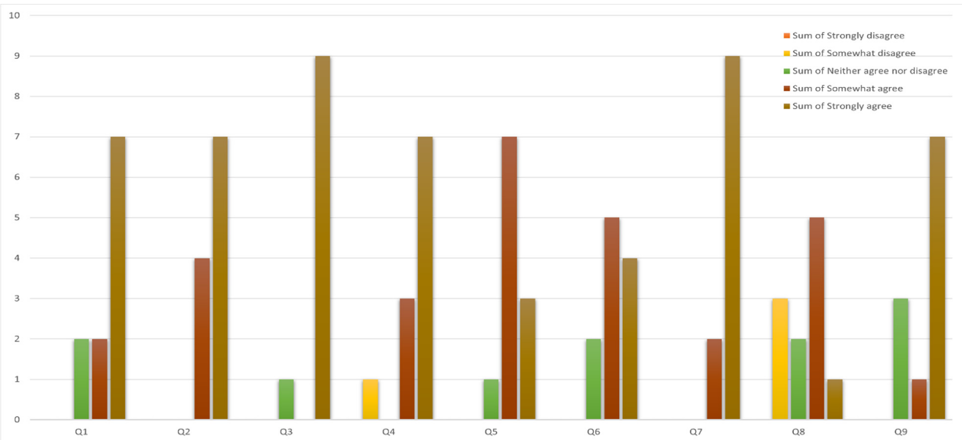


Figure 4. This bar chart shows participants (n = 11) response to questionnaire items (see Table 3) scored on 5-scale Likert (strongly disagree = 1, somewhat disagree = 2, neither agree nor disagree = 3, somewhat agree = 4, and strongly agree = 5).

5.1. Collaboration (Social Interaction)

In Section 3.1, we hypothesised that collaborative interaction in mixed reality will have a positive effect on engagement, collaboration (social interaction), and contextual relationship between users and the virtual environment. Participants response to the survey items *"It was easy for me to collaborate with the person I shared the mixed reality experience with"*, *"It was easy for me to share and explain what I was seeing"*, *"It was easy for me to use speech command to interact with the system"*, and "*It was easy for me to use gesture command to interact with the system*" were used to validate weather collaborative and multi-modal interaction methods enable collaboration (social interaction) in mixed reality. The results (see Table 3 and Figure 4) indicate that the collaborative and multi-modal aspects of the mixed reality experience enable collaboration (social interaction) between users. Furthermore, participants response to a question *"were the two of you able to communicate while exploring the shared mixed reality experience?"* validates the importance of collaboration (social interaction).

For instance, one participant responded to the question saying *" ... I think it's good when people get along. They communicate in all forms from experience, communication is an important thing for the experience ... "*

Similarly, the following responses from the participants underline the role collaboration plays in terms of enhancing visiting experience and cultural learning.

Participant 2. *" ... I would agree with what (name omitted) said in her interview, that it's good to have that level of communication. So, if this was like a partner experience that two people were able to do ... "*

Participant 3. *" ... I think If you knew each other, the interaction is easier. I'm not saying that strangers couldn't do it. But I'm just saying it's easier if you knew that ... "*

Participant 4. *" ... wasn't actually aware we were supposed to. Yeah, I was just sort of acting by myself ... "*

Participant 5. *" ... It was very easy. And that was also because we work together? If it was two strangers that were working together on it, it might not be quite as, as easily as intuitive ... "*

Participant 6. *" ... always ... "*

Participant 7. *" ... we didn't have any collaborative experiences ... that's because the application or the experience was already loaded ... "*

Participant 8. *" ... Yeah, look, it was because you, you know that you can see them there. And you can ask, well, how did you get there?"*

Participant 9. *" ... I tried to communicate with (name omitted) and he was in his own little world ... "*

Participant 10. *" ... I think for me, because it was kind of challenging anyway, because I tried to make it work. I was focused more on what I was experiencing. I noticed that the first two ladies seem to interact quite well ... "*

Hence, based on the results obtained from the survey items and interviews, we can validate that collaborative and multi-modal interaction methods in mixed reality have positive effects on social interaction and engagement.

5.2. Engagement

Participants' response to the survey items *"It was easy for me to collaborate with the person I shared the mixed reality experience with"*, *"It was easy for me to share and explain what I was seeing"*, *"I enjoyed this shared mixed reality experience"*, *"It was easy for me to relate the virtual experience with physical items in the gallery"*, *"It was easy for me to use speech command to interact with the system"*, and "*It was easy for me to use gesture command to interact with the system*" were used to validate weather collaborative and multi-modal interaction methods enable engagement in mixed reality. The results (see Table 3 and Figure 4) indicate that collaborative and multi-modal interaction methods in mixed reality enhance users' engagement. In addition, participants response to the questions *"were the two of you able to communicate while exploring the shared mixed reality experience?"* and *"were you able to interact with the system using all modes of interaction, such as gaze, speech, and gesture?"* indicate that collaborative and multi-modal interaction methods enhance users' engagement in mixed reality environment.

For instance, one participant stated that *"I think having that combination (gesture and speech) is good, especially for people with disabilities".* This statement shows the role that the multi-modal interaction method plays in terms of disseminating a mixed reality experience to people with different abilities and backgrounds. The following responses from participants support our assumption that a multi-modal interaction method enhances users' engagement with a mixed reality environment.

Participant 2. *" … Yes. I think it's good to have the two options (gesture and speech), not just one … "*

Participant 3. *" … it was fairly user friendly. For me, at least, the speech commands didn't work all the time. But people do always have that backup gesture … "*

Participant 4. *" … is quite easy to use gestures. I can see where the voice can be easier to use, but a lot of people use the gestures … "*

Participant 5. *" … I found the hand gestures difficult until I've got used to them. But I think having that combination is good, especially for people with disabilities. So, they can choose either the gaze or the spoken word … "*

Participant 6. *" … both, but I found the gesture was better than the speech. I had to say the keywords a couple of times … "*

Participant 7. *" … gestures were good … "*

Participant 8. *" … I was able to use speech freely … didn't experience any difficulty with that at … "*

Participant 9. *" … gestures, it's quite easy to use gestures. The voice command, have tried a few times … "*

Participant 10. *" … gestures … in the beginning I was a little confused … "*

Participant 11. *" … the gestures, once I learned them … "*

Based on the results obtained from the survey items and interviews, we can validate that collaborative and multi-modal interaction methods in mixed reality have positive effects on engagement.

5.3. Contextual Relationship

Contextual relationship refers to establishing a specific relationship between users, cultural context, and the immersive reality systems. In Section 3, we have hypothesised that collaborative interaction in mixed reality will have a positive effect on contextual relationship. Participants' response to the survey items *"It was easy for me to collaborate with the person I shared the mixed reality experience with"*, and *"It was easy for me to relate the virtual experience with physical items in the gallery"* were used to validate whether the collaborative interaction method enables a contextual relationship in mixed reality. The results (see Table 2 and Figure 4) indicate that collaborative interaction in mixed reality enables a contextual relationship. The results from Sections 5.2 and 5.3 can support this view because a contextual relationship is the result of collaborative and multi-modal interaction.

5.4. Enhanced Cultural Learning

In this paper, we have argued that collaboration (social interaction), engagement, and a contextual relationship in mixed reality enhance cultural learning in virtual learning.

The results presented above show that collaborative and multi-modal interaction methods enable these characteristics. Therefore, we can conclude that collaborative and multi-modal mixed reality has a positive effect on cultural learning in virtual heritage. Furthermore, this assumption is validated by participants' response to survey items *"I would like to see more items from the gallery presented in the system"* and *"I think the experience can enhance visitors' interest to explore more collections in the museum"* and their response to the question *"do you think this technology can be used to enhance visitors' interest in the museums' collections"*.

The following responses from the participants validate that the collaborative and multi-modal mixed reality enhances visitors' interest in learning about the museums' collection.

Participant 1. *" … Yeah, I can see how it's quite useful. You know, everybody likes a more interactive experience the museum … "*

Participant 2. *" … Yeah, I think so. It would engage the younger generations, including teenagers, I think we missed that demography from the museum, you know, the late teens, early 20s … "*

Participant 3. *" … I think this captures the interest of the 16- to 24-year-old. I think this is a great option to do that … "*

Participant 4. *" … because you have so many ways of learning. Some people are happy to read. Other people want to touch and interact with some people or technology as well. So, I think the experience adds another good layer … "*

Participant 5. *" … I think this would really appeal to young people. This gallery is underused and undervalued, this technology can attract young people to come to the gallery … "*

Participant 6. *" … yes, very much so … "*

Participant 7. *" … yes it can … "*

Participant 8. *" … Absolutely, this is a great new way of seeing gallery interviews and stuff. I really liked that … "*

Participant 9. *" … yes, the gallery, yes … "*

Participant 10. *" … I think it should. I mean, why wouldn't it? Because it's supposed to be enhancing your experience? Yes. So therefore, it must be beneficial … "*

Participant 11. *"...yes, absolutely"*

6. Discussion

The objective of this study was to validate whether collaborative and multi-modal mixed reality can facilitate enhanced cultural learning in virtual heritage. Overall, the finding supports our proposed hypotheses that collaboration (social interaction), engagement, and contextual relationship in mixed reality influence cultural learning in virtual heritage. However, the study's findings also identify some limitations that hinder the learning experience. These limitations are categorised into two groups, multi-media content (cultural context) and usability.

6.1. Multi-Media Content

Participants were asked to provide and share any thought or comment about their experience (only five participants responded to this open question). Their response suggest that the experience needs improvement in terms of the multi-media content and 3D models included in the experience. The following suggestions were made by the participants. We believe that addressing this feedback will improve the overall cultural learning in the mixed reality experience.

Participant 1. *" … I think subtitles during the video would be great. Also, a visual representation of what the whole ship looks like … "*

Participant 2. *" . . . reduce amount of text and video content. Currently it is quite long and may not hold visitors' attention . . . "*

Participant 3. *" . . . The video of the discovery of Xanth-would be good if a time display was shown so people know how long to expect it to go for and perhaps a volume control, as with other people in the gallery it was hard to hear . . .*

Participant 4. *" . . . Perhaps include a 3D version of entire Xantho when it was complete . . . "*

Participant 5. *" . . . Perhaps an animation of how the engine worked, and some further interpretation of why the sideways mounting of it was so remarkable . . . "*

6.2. Usability

Feedback received from participants suggests that visitors might find interacting with the system a difficult task. This is supported by the results of the evaluation. The results of the survey item *"I think visitors will find the system easy to use and follow"* received the lowest score compared to the other items. This is to some extent influenced by a lack of previous experience with immersive reality and Microsoft HoloLens in particular. Table 2 shows that a total 8 out of 11 participants had never used Microsoft HoloLens prior to the evaluation session. The following remarks were made by the participants.

Participant 1. *" . . . Interesting and worthwhile experience, easier I would think for younger people . . . "*

Participant 2. *" . . . Instructions embedded to explain ability to enlarge the 3D engine . . . "*

Participant 3. *" . . . Number the steps that participants should follow. If map could be mounted horizontally rather than on the floor (which I liked because it tracks the journey in the correct orientation, but was hard on the neck as I had to look down quite sharply) . . . "*

Based on the evaluation results and the remarks from participants, the interaction design needs improvement to address the suggestions. Visitors need to be presented with easy-to-understand instructions prior to engaging with the experience. The mixed reality application had a segment that provides instructions to users. However, the instructions were part of the experience. They need to be presented to users before the experience begins. To this effect, printed material or a video that demonstrates interaction methods of HoloLens can be used to introduce users to the overall experience.

7. Conclusions

In this paper, we have presented results of the evaluation of a clouds-based collaborative and multi-modal mixed reality application that took place at Western Australia Shipwreck Museum. The application was designed and implemented, aiming at enhancing cultural learning in virtual heritage via a combination of collaborative interaction, multimodal interaction, and mixed reality. SS Xantho, one of the world's first iron ships and western Australia's first coastal steamer, was used as a cultural context for the evaluation. Surveys and interviews were conducted to gather data from 11 participants. The collected data were analysed to validate whether collaboration, engagement, and a contextual relationship in mixed reality enhance cultural learning in virtual heritage. The results indicate that these characteristics facilitate enhanced cultural learning in virtual heritage. Furthermore, the results were interpreted to identify limitations, suggestions, and direction for future research in the domain.

Future Directions

Immersive reality display technologies, more specifically the Microsoft HoloLens, are expensive to install in museums as permanent exhibits. Even if the mixed reality application in this article is Microsoft HoloLens native application, it can be customised and deployed to other AR/MR headsets. Alternatively, the application can be customised for cloud native deployment. For instance, Amazon Web Services have released a cloud-based AR/VR platform called Amazon Sumerian. This platform enables museums to create, deploy, and run browser-based 3D, AR and VR applications. Museums can exploit this platform to disseminate their AR and VR experiences to a wider global audience. Hence, this article sets its future research focus on customising the mixed reality applications for multi-device and cloud deployment.

One of the findings of the evaluation was the difficulty of interacting with Microsoft HoloLens for first time users. Participants of the evaluation (experts, curators, and museum professionals) suggested that the general audience of museums (visitors of various background) would find the interaction mechanism (gesture, gaze, and speech) of HoloLens difficult to operate without prior knowledge and practice. They have also suggested that the younger generation would find the interaction mechanism relatively easy to learn. Hence, this article sets its future research direction on designing an interaction mechanism that is easy to learn and that accommodates different demographics of visitors.

Supplementary Materials: The following are available online at https://cultural-dataset.s3.ap-southeast-2.amazonaws.com/xantho/video/XanthoMR.mp4 (accesed on 29 October 2021), Interested readers can visit the link provided to access the video file that shows how the built prototype functions.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The web platform source code, and the survey results data presented in the research article are available on request from the corresponding author.

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Chapter 9

Conclusion

This thesis has examined the influence of collaboration (social interaction), engaging experience, and contextual relationship on cultural learning in a collaborative and multi-modal Mixed Reality (MR) heritage environment. To this end, the thesis attempted to explore immersive reality technology, interaction methods, interaction design, virtual heritage, and cultural learning categorised into four research phases. The primary objective of these research phases, and their theoretical and practical contributions are summarised in this chapter.

The first research phase of the thesis (see Chapter 2), attempted to discuss different categories of immersive reality technology (AR, VR, AV, and MR) and their enabling technologies from a VH perspective. It has also attempted to compare these immersive reality categories against their potential to establish a contextual relationship between users, reality, and virtuality and their capability to enable collaboration and engagement in virtual environments. It has attempted a similar comparison on different interaction methods (tangible, collaborative, multi-modal, sensor-based, device-based, and hybrid interfaces) in order to identify the best approach from an experiential and technological requirements perspective. Following the comparison, this research phase identified MR and VR as potential categories of immersive reality with the capability to enhance cultural learning in VH. From the interaction point of view, collaborative and multi-modal interaction methods were identified as the ideal choice to enhance cultural learning. Based on the comparison, this research phase proposed a specific combination of MR and a hybrid interaction method comprising collaborative and multi-modal features in order to enhance cultural learning at heritage sites and museums. This specific combination was identified as a practical approach for VH applications to establish a contextual relationship between users and cultural context and implement collaborative experience to add a social dimension to the MR experience.

The second research phase has attempted to identify major gaps in existing definitions of the reality-virtuality continuum and its segments (see Chapter 3) and presented a redefinition of the continuum from a perspective underlining the contextual relationship and interaction between users, reality and virtuality with a special focus dedicated to MR. Following that, this research phase has presented different perceptions of MR, especially in the VH domain (see Chapter 4). It has also outlined a boundary between AR and MR before attempting to answer the key question raised in the research phase 'Is MR a bridge between two worlds or a fusion of two worlds?'

The third research phase has attempted to present a complete workflow for experiencing a 3D model in a mixed reality environment captured from real-world objects by using proprietary and open access software and service (see Chapter 5 and Figure 9.1). The workflow starts with digitising 3D artefacts based on image-based photo modelling (photogrammetry), converting the 3D point cloud to a 3D mesh, saving and sharing the 3D model to an online repository, viewing the 3D model in VR/AR, and finally deploying the 3D content to a mixed reality environment (Microsoft HoloLens) and interacting with the virtual content. The workflow was demonstrated to fourteen participants in a workshop session, and users' feedback was collected. Users' feedback validated the workflow as easy to learn, workable and effective; with a few minor technical issues. Following the demonstration, the research phase designed and implemented a novel map-based interaction interface, namely Walkable Mixed Reality (MR) Map (see Chapter 6). The main objective of the application was enhancing cultural learning in VH applications by enabling a contextual relationship and interaction between users, immersive reality technologies and cultural context. The application was then extended to a clouds-based collaborative and multi-modal MR heritage environment (see Chapter 7 and Figure 9.2). Similar to the Walkable Mixed Reality Map, the primary objective of the clouds-based collaborative and multi-modal MR application was enhancing cultural learning through an engagement, a contextual relationship, and an interactive virtual environment. The implementation has utilised cloud services, such as Amazon Polly, Amazon S3, Azure Spatial Anchors, Azure Cosmos DB, and Azure App Service. In addition to cloud services, the implementation has also exploited immersive reality technology (specifically, Microsoft HoloLens) and development tools and platforms, such as Unity, Mixed Reality Toolkit, Azure Spatial Anchors SDK, and Microsoft Visual Studio. SS Xantho (see Section 1.9), one of the world's first iron ships and Western Australia's first coastal steamer, was used as a case study for the prototype.

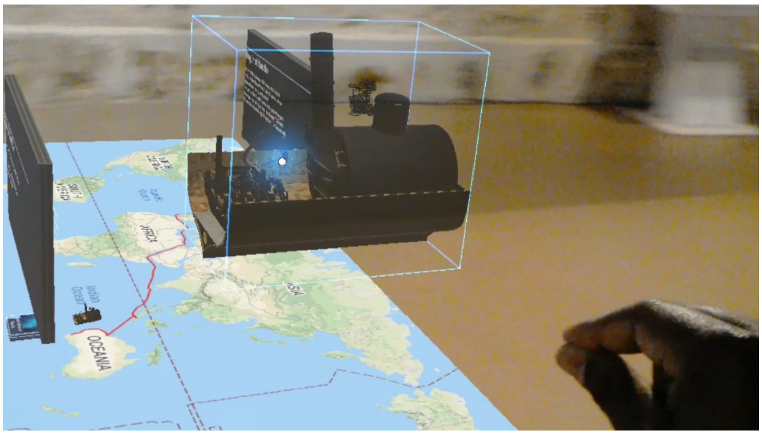

Figure 9.1: Walkable Mixed Reality Map.

The final research phase (phase four) has presented results of evaluation of the clouds-based collaborative and multi-modal mixed reality application that took place at Western Australia Shipwreck Museum (see Chapter 8). The application was designed and implemented aiming at enhancing cultural learning in virtual heritage via a combination of collaborative interaction, multi-modal interaction, and mixed reality. A Survey and interviews were conducted to gather data from 11 experts. The collected data was analysed to validate whether collaboration, engagement and contextual relationship in mixed reality enhance cultural learning in virtual heritage. The results indicated that these characteristics facilitated enhanced cultural learning in virtual heritage. Furthermore, the results were interpreted to identify limitations, suggestions, and direction for future research in the domain (further discussed in Section 9.2).

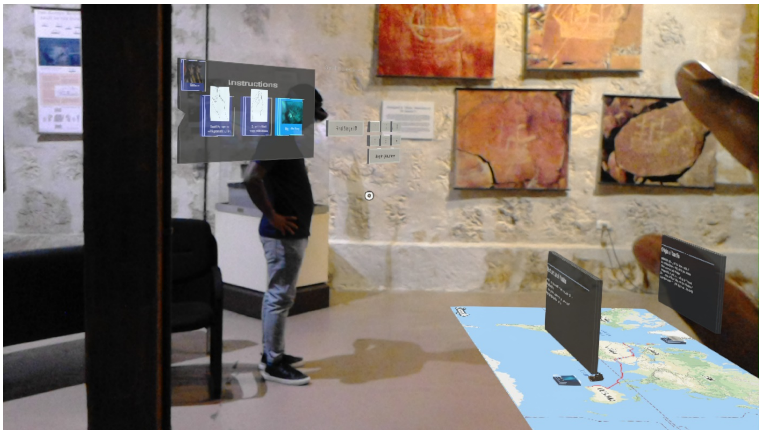

Figure 9.2: Users interacting with the clouds-based collaborative and multi-modal mixed reality application

9.1 Contribution

This thesis has contributed to both theoretical and practical aspects of VH. In terms of the theoretical aspect, this thesis can be considered as an addition to the existing knowledge area in VH that promotes cultural learning as the primary focus of immersive reality applications across different themes. In addition, the thesis has made visible contributions to practical aspects of VH, especially to interaction design and method, presentation (immersive reality), computing resource aspects of the domain.

1. **Interaction design/method**: Interaction design and method play an important role in VH in terms of enabling cultural learning. This thesis has attempted to validate the premise that collaborative and multi-modal interaction methods are capable of achieving this goal.

2. **Walkable Mixed Reality map as interaction interface**: Walkable Mixed Reality Map is one of the novel contributions of this thesis. Maps add a spatio-temporal dimension to storytelling, presentation, and visualisation of heritage assets in VH. Walkable, immersive, and interactive maps are engaging and relatable. These characteristics enrich visual information presentation with engaging and immersive aspects in the context of both spatial and thematic perspectives. Hence, this approach is a contribution towards extending the existing expertise that tackles the technical challenges of combining geospatial information and immersive reality technologies across various domains.

3. **Cloud computing for virtual heritage**: Another novel contribution, the thesis has made is demonstrating the capability and benefits of cloud computing for MR application deployment in VH domain. The thesis has demonstrated cloud computing technology's ability for fast development and deployment while increasing performance and reducing cost of computing resources.

9.2 Summary and Future Directions

Enhancing cultural learning in VH applications was the main objective of this thesis. To this end, it has attempted to explore, design, implement and evaluate interaction methods and immersive reality technology from a perspective that emphasised the importance of collaboration (social interaction), engaging experience, and contextual relationship in MR heritage environment.

The evaluation phase of this PhD research has revealed two important limitations. The first limitation raised by experts who participated in the evaluation relates to the cost and expertise required to design, develop, and maintain MR application. The second limitation relates to the difficulty of interaction methods (Microsoft HoloLens) for new users. Based on these limitations, the following research directions have been set for further exploration.

1. **Cost and expertise:** Immersive reality display technologies, more specifically the Microsoft HoloLens, are expensive to install in museums as permanent exhibits. This is perhaps one of the reasons why the technology is not widely adopted by museums. Chapter 6 has discussed alternative MR display technologies and their relative capabilities. For instance, HoloKit [1] and Vufine AR Kit [2] are much cheaper AR/MR headsets, \$35 and \$10 respectively, compared to Microsoft HoloLens that currently costs \$3,500. However, their capability is very limited as the headsets require compatible smartphones. HoloLens, on the other hand, comes with its own computing resources. Even if the mixed reality application designed and implemented in this thesis are Microsoft HoloLens native applications, they can be customised and deployed to other AR/MR headsets. Alternatively, the applications can be customised for cloud native deployment. For instance, Amazon Web Services have released a could-based AR/VR platform called Amazon Sumerian [3]. This platform enables museums to create, deploy, and run browser-based 3D, AR and VR applications. Museums can exploit this platform to disseminate their AR and VR experiences to a wider global audience. Hence, this thesis sets its future research focus on customising the mixed reality applications for multi-device and cloud deployment.

[1] https://holokit.io/
[2] https://store.vufine.com/products/vufine-ar-kit
[3] https://aws.amazon.com/sumerian/

2. **Difficulty of interaction in Mixed Reality (Microsoft HoloLens):** One of the findings of the evaluation phase of this thesis was the difficulty of interacting with Microsoft HoloLens for fist time users. Participants of the evaluation (experts, curators, and museum professionals) suggested that the general audience of museums (visitors of various background) would find the interaction mechanism (gesture, gaze, and speech) of HoloLens difficult to operate without prior knowledge and practice. They have also suggested that the younger generation would find the interaction mechanism relatively easy to learn. Hence, this thesis sets its future research direction on designing interaction mechanism that is easy to learn and that accommodates different demographics of visitors.

Appendices

Appendix A

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†These authors have contributed equally to this work

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Author: Hafizur Rahaman,Erik Champion,Mafkereseb Bekele
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