MRes Thesis

Transforming Museum Exhibits using Interactive Mixed-Reality

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Abstract

Museums play a crucial role in preserving and communicating cultural, historical, and scientific knowledge. However, traditional exhibition methods often limit visitor engagement and comprehension. This research investigates how mixed-reality (XR) technologies (integrated with Artificial Intelligence (AI) and Computer Graphics (CG)) can transform visitor experiences within museum environments, with a focus on the Hunterian Museum's Science Collection.

Building on these insights, a prototype mobile and mixed-reality application was designed and developed to enable immersive exploration of artefacts in 3D, interactive storytelling, and adaptive learning experiences. The system architecture integrated wearable interfaces, edge computing, cloud services, and AI-driven modules for speech recognition, natural language processing, and personalized recommendations.

After finishing the implementation of my App, functional and performance evaluations are operated. It identified optimal solutions for enabling natural user interaction, while user studies demonstrated significant improvements in engagement, comprehension, and satisfaction compared to traditional exhibition methods. The findings indicate that AI-enhanced XR applications can provide inclusive, dynamic, and educational museum experiences, bridging the gap between physical artefacts and visitor understanding. This research contributes a practical framework for integrating immersive technologies into museum practice and offers insights for future developments in adaptive, user-centered digital heritage experiences.

Contents

Chapter 1: Introduction

1.1 Background

Museums serve as vital institutions for the preservation, communication, and interpretation of cultural, historical, and scientific knowledge. They play an essential role in education, research, and public engagement by providing access to both tangible and intangible heritage. Traditionally, museum visitors engage with artefacts primarily through static information panels and labels. While this approach offers valuable insights, it often limits the level of interaction and immersion that visitors experience. The Hunterian Museum, like many others, faces challenges in providing interactive and visually rich engagement opportunities for visitors. Despite hosting thousands of visitors monthly, the museum's exhibits offer limited avenues for digital or personalized exploration, particularly in three-dimensional (3D) contexts. Consequently, visitors may struggle to fully comprehend the artefacts' scientific or cultural significance, especially when staff are unavailable to provide contextual explanations.

Recent technological developments in Extended Reality (XR) (as a term that encompasses Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR)) have opened up new possibilities for redefining how museums present and communicate their collections [12, 14]. Augmented Reality (AR) enhances the user's real-world environment by overlaying digital elements such as images, text, animations, or 3D models onto physical surroundings [26]. Virtual Reality (VR), in contrast, places users within a completely computer-generated environment, isolating them from the physical world [46]. Mixed Reality (MR) bridges the gap between AR and VR by seamlessly integrating real and virtual elements, allowing users to interact with digital objects as if they were physically present in the same space. Collectively, XR technologies offer transformative opportunities for museums by enhancing visitor engagement, learning, and accessibility. They allow for interactive storytelling, where visitors actively explore narratives rather than passively read information [50]. XR can also visualize complex scientific or historical processes that are otherwise difficult to convey through static displays, such as the operation of scientific instruments or the reconstruction of archaeological sites [55]. Furthermore, these technologies support personalized learning experiences, adapting content based on visitor interests or knowledge levels. By bridging the physical and digital realms, XR technologies not only modernize museum exhibitions but also foster deeper emotional and cognitive connections between visitors and cultural heritage [6, 10].

Although the application of XR in museums is still in its early stages, institutions are increasingly experimenting with these tools to enhance interactivity and accessibility of museum exhibitions. As awareness grows about their potential, it is anticipated that more cultural organizations will integrate XR systems to attract diverse audiences and foster deeper connections with cultural heritage.

1.2 Motivation

The motivation for this research stems from the growing need to make museum exhibits more interactive, informative, and inclusive through digital transformation. Visitors today expect engaging, technology-driven experiences that go beyond passive observation. This expectation has intensified in the post-COVID-19 era, where digital interaction has become an essential part of everyday life ([2]).

The Hunterian Museum's Science Collection provides a compelling context for exploring how digital technologies can bridge the gap between visitors and artefacts. Many of these artefacts represent complex scientific concepts that are difficult to convey through traditional display methods. By introducing interactive, mixed-reality experiences, museums can help visitors understand *how* and *why* these artefacts function—transforming passive observation into active exploration.

Moreover, integrating technologies such as digital twins, artificial intelligence (AI), and mixed reality (MR) has the potential to redefine how visitors engage with museums. Digital twins—virtual replicas of physical artefacts—can allow users to interact with, manipulate, and explore exhibits in 3D, even revealing hidden internal mechanisms. When combined with AI-driven personalization and MR visualization, such systems can make museum experiences more adaptive, immersive, and educational.

1.3 Research Aim and Questions

The overarching aim of this research is to investigate how mixed-reality technologies can transform visitor engagement and learning in museum environments, with a specific focus on the Hunterian Museum's Science Collection. To achieve this aim, the study addresses the following research questions:

1. How can mixed-reality technologies be integrated into museum exhibits to enhance interactivity and visitor engagement?
2. Whether my design principles and interaction models can effectively support immersive learning experiences in museums?
3. What are the technical, operational, and ethical challenges associated with deploying mixed-reality systems in museum contexts?

1.4 Research Objectives

To address the research questions outlined above, this study establishes several key objectives that define its scope and direction.

The first objective is to analyse the current limitations of interactive engagement in museum exhibitions, focusing on visitor behaviour, learning needs and patterns of engagement with artefacts. This analysis will provide insights into how digital and immersive tools can enhance understanding and participation within museum contexts. Building on this foundation, the second objective is to design and develop a prototype mobile and mixed-reality App that integrates artificial intelligence (AI) to create an immersive, interactive experience. The app will be specifically designed for the Hunterian Museum's Science Collection, enabling visitors to explore artefacts in 3D, access contextual information, and interact with virtual representations of the exhibits. The third objective is to evaluate the effectiveness of the developed app in enhancing visitor engagement, comprehension, and satisfaction. Through user studies, observations, and feedback collection, the research will assess the system's impact on learning outcomes and user experience compared to traditional exhibition methods.

1.5 Structure of Thesis

This thesis is structured into six chapters, as follows:

First, *Chapter 1 Introduction* provides the research background, motivation, objectives, and structure of the study. Then, *Chapter 2 Literature Review* reviews previous work on XR and interactive technologies in museums, which is to identify research gaps in previous research. *Chapter 3 System Design* presents the complete design and development process of the proposed application. It outlines the conceptual framework, system architecture, and technical components used to build the mixed-reality solution. *Chapter 4 Results of Functional Test and User Evaluation* presents the results from user testing and data analysis, evaluating the system's effectiveness in enhancing user engagement by personalized information tailoring. *Chapter 5 Conclusion* will summarize key findings, discusses implications for museums and heritage institutions, which finds lead to propose directions for future research.

Chapter 2 Literature Review

2.1 Introduction

This chapter would review the existing body of literature related to the use of XR technologies within the context of museum exhibitions. It helps to understand how XR has been adopted to enhance visitor engagement, learning, and interaction. Following this, the critical analysis is conducted to examine the shortcomings and constraints of current XR implementations. These include technological barriers, limited realism in visual representation, ethical considerations and so. By evaluating these limitations, the discussion reveals the gaps in existing approaches that hinder the delivery of immersive experiences. In response to these identified gaps, the final section of the chapter discussed how Artificial Intelligence (AI) and Computer Graphics (CG) technologies can be applied to overcome these challenges and advance the field of XR in museum contexts.

2.2 Review on XR Methods used in Exhibitions and their benefits

The application of XR in museum exhibitions has produced a range of benefits that can be grouped into four key areas: the enhancement of educational experiences, the augmentation of visitor engagement and the expansion of accessibility and inclusivity. Each of these areas represents a crucial dimension of how XR technologies can transform traditional museum practices into more participatory, immersive, and inclusive experiences. The following sections critically examine these dimensions by reviewing current studies and practical implementations of XR systems in museum and cultural heritage contexts.

2.2.1 Enhancement of Educational Experiences

The integration of Augmented Reality (AR) and Virtual Reality (VR) technologies in educational and cultural settings is increasingly recognized for its potential to enhance learning experiences. A notable example is the study by Sugiura et al., which introduces three AR-based systems to improve learning in medical specimen museums, including a head-mounted display system that facilitates natural interaction with virtual objects [59]. This approach is echoed in a 2022 study by Mikami et al., which presents an Extended Reality (XR) visualization workflow for ancient museum specimens, leveraging VR to provide flexible, remote education opportunities. This study highlights the use of platforms like Rad3D and Sketchfab to aid medical students' understanding of anatomy and embryology, despite acknowledging challenges related to cost and access [44]. Similarly, the application of VR in the exhibition of agricultural tools is explored by Yang et al. Their research introduces a novel method for virtual interactive displays, combining static displays with dynamic, interactive experiences. This approach not only enhances the exhibition of agricultural tools but also provides insights into their use and inherent wisdom. To address the challenges in human-computer interaction, the study proposes technologies such as intelligent scene switching and interactive virtual roaming, aiming to create a more immersive and user-friendly experience [70]. In the context of museums, the educational impact of AR is further demonstrated in the AR video game 'Horus' (figure 2.1), designed to enhance visitors' experiences with museum content [26]. Extending this notion, the VR museum application *2gether VM* showcases how VR can be used to facilitate understanding of cultural heritage through experiential learning. This application, developed for a contemporary art museum, highlights how users engaged with VR-based content and were inclined to recommend it to others, underscoring the potential of VR in cultural heritage communication [62].

Figure 2.1 The 'Horus' game mock-up (source: [26])

Discussion

While XR technologies have demonstrated significant potential in enriching museum-based learning, several shortcomings still limit their educational effectiveness. One of the primary issues is the lack of adaptive learning mechanisms within most XR applications. Many current systems provide a one-size-fits-all experience, offering the same level of content and interaction to all visitors regardless of their prior knowledge, interests, or learning pace. This static approach can result in cognitive overload for novice users or insufficient depth for expert learners, thereby reducing educational impact. Additionally, XR experiences often prioritize visual immersion over pedagogical structure, focusing on realism and interactivity without adequately supporting knowledge retention or conceptual understanding. Another limitation lies in the accuracy and realism of digital representations, which can directly affect how visitors interpret scientific or cultural artefacts. Simplified 3D models or generic animations may fail to capture the detailed characteristics or contextual significance of the exhibits, leading to superficial engagement rather than deep learning. Moreover, the lack of real-time feedback and intelligent guidance within XR systems means that users may interact with virtual content without fully understanding its meaning or relevance.

2.2.2 Augmentation of Visitor Engagement

XR methods impacted augmentation of Visitor Engagement in two ways of *Interactive Exhibits* and *Digital Augmentation of Exhibits*.

Interactive Exhibits

In this field, it can create the Mixed Reality Exhibits. The integration of virtual content with tangible entities in museums and cultural heritage sites is a rapidly evolving area of research, offering visitors multi-dimensional interactive experiences. A prominent example of this is the Thresholds project, a virtual reality (VR) recreation of the world's first photographic exhibition. This project exemplifies large-scale technology integration, where VR architecture effectively overlays virtual and physical spaces, combining tactile sensations, movement, visual, and audio stimuli. The key to its success is the layering of a virtual model onto a physical set, which also includes innovative solutions for challenges like entering and exiting the experience and integrating the VR installation within each host museum's gallery space [60].

Figure 2.2 The VR touch museum. Left: User stands on an artificial grass surface while virtually outside. Right: The user feels the carpet when inside the ancient room ([73])

Zhao et al. experimented with combining VR and touch to enhance the sense of presence in virtual museums [73]. Similarly, Mann et al. introduced a method for museum exhibitions and cultural heritage preservation involving lifelike 3D printed replicas of artifacts (figure 2.2). These replicas are augmented using mixed reality technology to replicate the appearance of the original items, offering a more intimate interaction with cultural heritage and overcoming the traditional limitation of valuable artifacts being confined behind glass [42]. Additionally, innovative approaches to museum souvenirs have emerged, such as the AR Firework. This concept combines a physical firework launcher with an AR model, offering a unique, interactive experience [32]. Another significant contribution is the mixed reality installation created by Vosinakis et al. for the Museum of Marble Crafts on Tinos Island, Greece. This installation immerses visitors in the role of crane operators in a virtual quarry, blending tangible and intangible heritage elements. Users interact with the exhibit using tangible controllers, while their actions are mirrored by digital workers in a 3D environment, creating an engaging and educational experience [65].

Figure 2.3 Little L project: virtual colouring and taking photos with a smartphone (source: [8]).

Interactive Tour

Meanwhile it can also create Interactive Tour. Recent advancements in digital technologies have significantly enhanced interactive experiences in museums, with researchers exploring various innovative systems. Chen et al. developed a system that utilizes a camera to capture hand motions and guide images. This system offers real-time contextual information about 3D models of artifacts and multimedia materials, presenting a cost-effective and hygienic alternative to traditional tactile devices in public spaces [11]. In the realm of virtual reality (VR) exhibits, Barbieri et al. employed a user-cantered design (UCD) approach for developing a VR exhibit that allows visitors to view and manipulate the original context of 3D archaeological artifacts on a touchscreen. This study addresses the technical challenges in designing virtual museum exhibits with off-the-shelf technology, providing practical solutions for developing VR exhibits within the constraints of low budgets and limited space [8]. Similarly, the Little L Project, as described by Antlej et al., developed a mixed reality (MR) game that merges a haptic experience with immersive VR (figure 2.3). This interdisciplinary project focuses on palaeontology, enabling museum visitors to learn about dinosaur colours through scientifically accurate content, interactive learning, and creative exploration [5]. Beyond individual exhibits, there has been a focus on encouraging visitor engagement throughout entire museum tours. "Memories of Carvalhal's Palace – Haunted Encounters" is an Augmented Reality (AR) game designed for the Natural History Museum of Funchal. It integrates interactive AR with mobile gaming, prompting visitors to explore museum exhibits, collect scientific information, interact with 3D AR models, and unravel a mystery by locating the museum's scientific library [46]. Similarly, the "Seek Out Katipunan" project uses mobile AR devices to stimulate museum exploration. Visitors engage with the exhibits by scanning QR codes and other means, fostering a more interactive and informative experience [13].

Discussion

While XR technologies have significantly enhanced visitor engagement through interactive exhibits and the digital augmentation of artefacts, several limitations still hinder their full potential in sustaining meaningful and long-term engagement. Interactive exhibits, such as mixed-reality installations and VR reconstructions, can successfully attract visitor attention through novelty and immersion; however, they often fail to adapt dynamically to individual visitor behaviours or preferences. Current systems typically rely on pre-scripted interactions or static content, resulting in experiences that, although visually compelling, lack personalization and responsiveness. As a result, engagement tends to be short-lived and largely driven by sensory stimulation rather than intellectual curiosity or emotional connection.

Another key shortcoming is the limited realism and interactivity of digital augmentations. Although projects like *Thresholds* and the *VR Touch Museum* demonstrate innovative combinations of tactile and virtual stimuli, the sensory fidelity remains constrained by hardware capabilities and simplistic graphical representations. For instance, texture rendering, lighting realism, and haptic feedback are often insufficient to replicate the authentic material qualities of artefacts. Similarly, while 3D printed replicas enhanced by MR (as shown in Mann et al.'s work [42]) bridge the gap between tangible and virtual, these systems frequently struggle with precise alignment between digital overlays and physical objects, breaking immersion and reducing the perceived authenticity of the experience.

2.2.3 Expansion of Accessibility and Inclusivity

The use of Extended Reality (XR) technology provided a virtual museum visit experience, especially for those who are physically challenged or unable to visit in person. it will ensure that the intellectual and cultural experiences offered by the museums are accessible to all. Using Virtual Reality (VR) technology, viewers can experience a visit as if they were there at home, supporting distance learning programmes and research activities, thus broadening the accessibility and educational reach of museums.

Figure 2.4: The Virtual House Museum (VHM) was exhibited at three different museum settings: AEC VRLab: Museum guide introduces the installation to the VR player exclusively by talking to him/her. Spectators observe the interaction process via an overview display. KHM: Museum guide introduces the installation using the MR guidance tool. Spectators can follow via an overview display. AEC Deep Space: A Museum guide navigates the VR player through VHM.

The advancement of technology in museums has led to significant improvements in accessibility, particularly for individuals with disabilities. Ferracani et al. developed an immersive system specifically designed for users with mobility disabilities. This system, integrating voice commands and virtual reality (VR) technology, significantly enhances the inclusivity of virtual museums, enabling a more accessible experience for this demographic [18]. Additionally, tailored experiences have been created for senior visitors, addressing their unique needs and preferences in engaging with museum content [17]. Another noteworthy initiative is by Soccini et al., who developed a remote access application targeting a specific group of people who are typically unable to visit museums. They utilized an electric bus equipped with VR technology to provide a mobile museum experience. This innovative approach is particularly aimed at bringing the museum experience to individuals such as inmates in juvenile prisons. The study not only discusses the technical aspects of this solution but also delves into how museums can embody crucial values like accessibility, sustainability, and inclusiveness, thus broadening the scope of who can experience and enjoy museum exhibits [58].

"Livia's Villa Reloaded" is a virtual reality installation that recreates the Villa Ad Gallinas Albas. This archaeological site near Rome has been digitally reconstructed in 3D to depict its augustan era appearance. The VR application allows for mid-air gesture interactions, offering a unique storytelling experience blending real-time exploration, cinematic techniques, real actors, and virtual set practices. [52] Similarly, the study by Malinvern et al. used 3D reconstruction techniques to document and deepen the understanding of the large number of multicoloured mosaic floors within the site. The data was collated into a geodatabase, thus simplifying the exchange of information between different experts. Experts utilize GIS for in-depth analysis, while visitors engage with multimedia applications like Augmented Reality (AR) and high-resolution web visualization. [41] The study by Carvajal et al. Utilizes 3D image acquisition techniques like digital photogrammetry and computer 3D modelling, two virtual scenes were created as part of a digitization project for Argentine museums. The first, "Virtual Collections," is a computer-generated environment showcasing museum collections digitized via 3D photogrammetry. The second is an interactive virtual tour that recreates a retrospective exhibition, serving as a record of the event. Both utilize 3D modeling and texturing for realistic results [9].

Unlike creating a completely virtual environment, Venigalla et al. produced a prototype that displays a 3d model of an artefact on a mobile phone by recognising images of the artefact from a museum website. This approach has the benefit of being lightweight compared to other remote access applications [63]. The CubeMuseum is another lightweight attempt at augmented reality, providing a physical experience of a virtual museum collection. Using a simple, affordable cube and a smartphone app, users can interact with 3D representations of museum objects. The prototype provides valuable insights into the design of affordable interactive cultural heritage experiences [40]. The research by Banfi et al. focuses on creating 3D models for interactive virtual environments, aiming to enhance the presentation of archaeological findings from Rome's southeast suburbs. It involves developing a virtual museum for artifacts from the Appia Antica Archaeological Park, utilizing high-resolution 3D survey data and digital representation. The goal is to enrich both virtual and on-site experiences, effectively digitizing and communicating historical content, and facilitating the virtual relocation of artifacts for broader access and educational purposes [7]. Kersten et al. developed a similar virtual museum project for the "Alt-Segeberger Bürgerhaus" [34].

Discussions

Although Extended Reality (XR) technologies have considerably expanded access to museum experiences for individuals unable to visit in person, several challenges still impede their full inclusivity potential. Projects such as the *Virtual House Museum (VHM)* and *Ferracani et al.'s immersive VR system for users with disabilities* demonstrate meaningful strides toward accessible design. Similarly, initiatives like *Soccini et al.'s mobile VR museum bus* and *Venigalla et al.'s lightweight AR applications* show that remote and low-cost XR experiences can democratize cultural participation. However, these systems still face significant shortcomings related to usability, personalization, sensory inclusivity, and technological accessibility.

A major limitation arises from the one-dimensional nature of accessibility design in current XR systems. While many experiences offer virtual mobility or basic interaction through gestures or voice commands, they often fail to address the diversity of user needs, including sensory impairments (visual, auditory), cognitive differences, or age-related challenges. For example, most VR-based environments rely heavily on visual stimuli and head-mounted displays, which can exclude users with visual impairments or motion sensitivity. Furthermore, accessibility features tend to be additive rather than integrative, which is introduced as secondary options rather than being embedded into the design framework from the start. This results in inconsistent usability across devices and platforms. Another shortcoming lies in limited content adaptability and personalization. Current XR museum systems typically deliver the same digital experience to all users, regardless of their physical capabilities, learning preferences, or cultural backgrounds. This lack of adaptivity can reduce inclusivity by failing to account for different interaction styles or comprehension levels. Additionally, hardware dependency and high system requirements, such as expensive VR headsets or powerful computing equipment, pose further accessibility barriers, especially in low-resource or educational contexts.

2.3 Research gaps

As museums increasingly embrace XR technologies, the integration of Intelligent Mixed Reality (IMR) and Artificial Intelligence (AI) into museum apps holds immense potential for enhancing visitor engagement, learning outcomes, and the overall experience. However, alongside these exciting possibilities, several challenges have not been addressed to fully harness the benefits of XR and AI in cultural institutions. These challenges span across technical limitations and ethical concerns (figure 2.5).

First is for technical limitations. While XR technologies offer numerous benefits, their implementation in museums faces a number of technical limitations that hinder their widespread adoption. One of the most significant obstacles is the high cost of developing and implementing XR-based experiences. Hardware costs, including VR headsets, AR glasses, and motion-tracking devices, remain a barrier for many institutions, particularly smaller museums with limited budgets. The price of these technologies can be prohibitively expensive, especially when scaling XR experiences for large audiences or multiple exhibits. Additionally, the hardware dependency of XR technologies presents a logistical challenge. Many XR experiences require specialized equipment, which may not be accessible to all visitors. Museums may face difficulties in providing enough headsets or devices for high traffic periods, limiting access to these enhanced experiences. Although the development of mobile-based XR (AR experiences that can be accessed through smartphones) has mitigated some of these challenges, it still requires visitors to have access to suitable mobile devices and strong internet connectivity, which may not be universally available.

Another key issue in field of technical limitations is content development. Creating high-quality XR experiences requires substantial investment in both time and expertise. For example, museums must work with content creators, technologists, and AI experts to develop interactive and immersive experiences that are both engaging and educational. Furthermore, maintaining and updating XR content to keep it relevant and accurate is an ongoing challenge. In the case of AI-driven interactions, training AI systems to interpret user input and adapt the content accordingly adds an additional layer of complexity, requiring sophisticated machine learning models and large datasets.

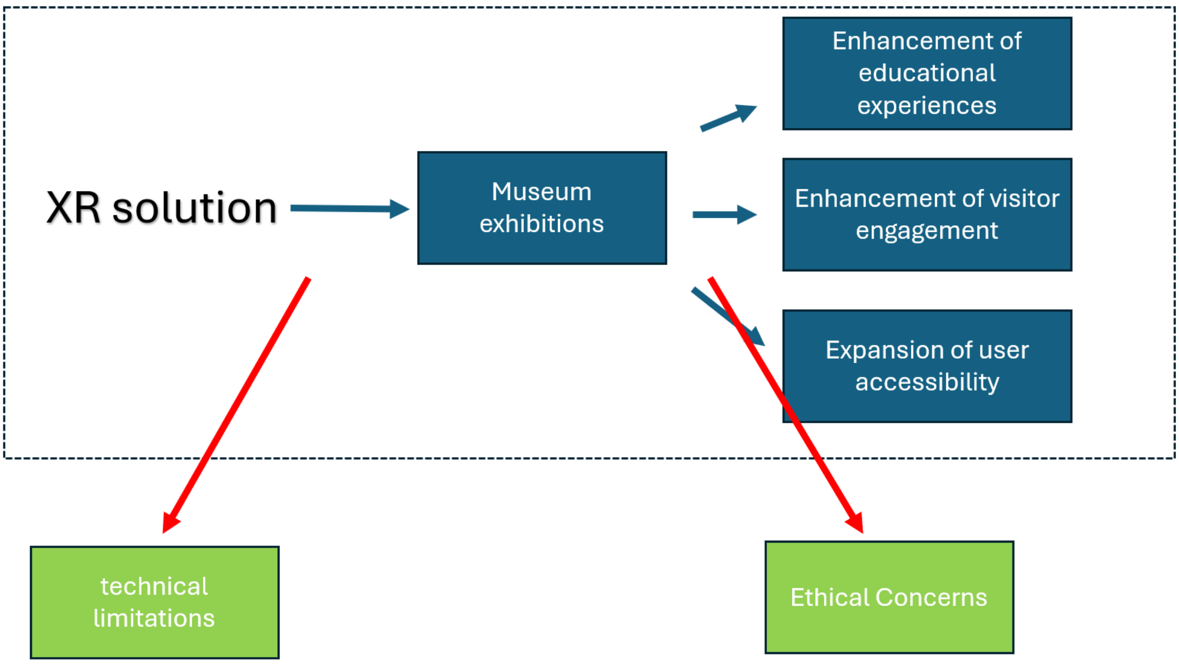

Figure 2.5 conceptual model for research gap

In field of Ethical Concerns, the use of XR in museums raises important issue related to data privacy and the authenticity of historical reconstructions, considering any technology that collects and processes user data. The integration of AI and machine learning into museum apps often involves collecting data on visitors' interactions, preferences, and behaviours within exhibits. While this data can be used to improve user experiences and tailor content, it also raises significant concerns regarding privacy and consent. Museums must ensure that they are transparent about how data is collected, used, and stored, and that they comply with relevant data protection laws (e.g., GDPR in the European Union). Moreover, the ability of XR technologies, especially AI and IMR, to create virtual reconstructions of historical sites and artifacts introduces questions about the authenticity of these representations. While XR can offer immersive, visually stunning recreations of lost or damaged artifacts, these virtual experiences may not always reflect the true historical context of the originals. There is a fine line between creative reconstruction and historical distortion, and museums must balance the desire for engaging, visually appealing content with the need for historical accuracy. Ethical considerations also include ensuring that the use of XR technologies respects cultural heritage and does not exploit or misrepresent sensitive topics or communities.

2.4 Implementation: Required improvement for new APP

To fulfil above gaps, I will develop a new App for museum exhibitions with Required improvement. Looking ahead, several future directions in XR technology hold great promise for improving museum experiences and overcoming current challenges. One key area of development is the integration of AI-driven adaptive XR systems. By leveraging AI, museums could create dynamic, personalized experiences that adapt to individual visitors' preferences, learning styles, and engagement levels. For example, AI could analyse a visitor's interaction history and adjust the content in real-time, offering personalized learning paths, guiding them to exhibits of particular interest, or providing contextual information tailored to their level of knowledge. Such intelligent systems would create a more engaging and meaningful experience, particularly in large museums with diverse collections.

Another exciting prospect for the future of XR in museums is the development of wearable interfaces. While VR headsets and AR glasses are already being used in some museum contexts, future advancements could lead to more comfortable and user-friendly wearable technologies. Lightweight, unobtrusive smart glasses or haptic feedback suits could allow visitors to engage with XR content seamlessly, without the need for bulky equipment or reliance on smartphones. These devices would offer a truly immersive experience, enabling visitors to interact with exhibits in novel and intuitive ways.

Chapter 3 System Design of my App

3.1 Introduction

This chapter presents the design and implementation of the proposed mixed-reality application for the Hunterian Museum's Science Collection. Its purpose is to provide a detailed account of how the app was conceptualized, developed, and deployed to enhance visitor engagement and interactivity for museum exhibitions. In this chapter, it described the system architecture, hardware and software components, user interface design, which help to adopt the integration of artificial intelligence (AI) and computer graphics (CG). By developing its App, this chapter demonstrates how the app transforms traditional museum experiences into user experience with immersive, interactive, and personalized contents.

3.2 System architecture of my App

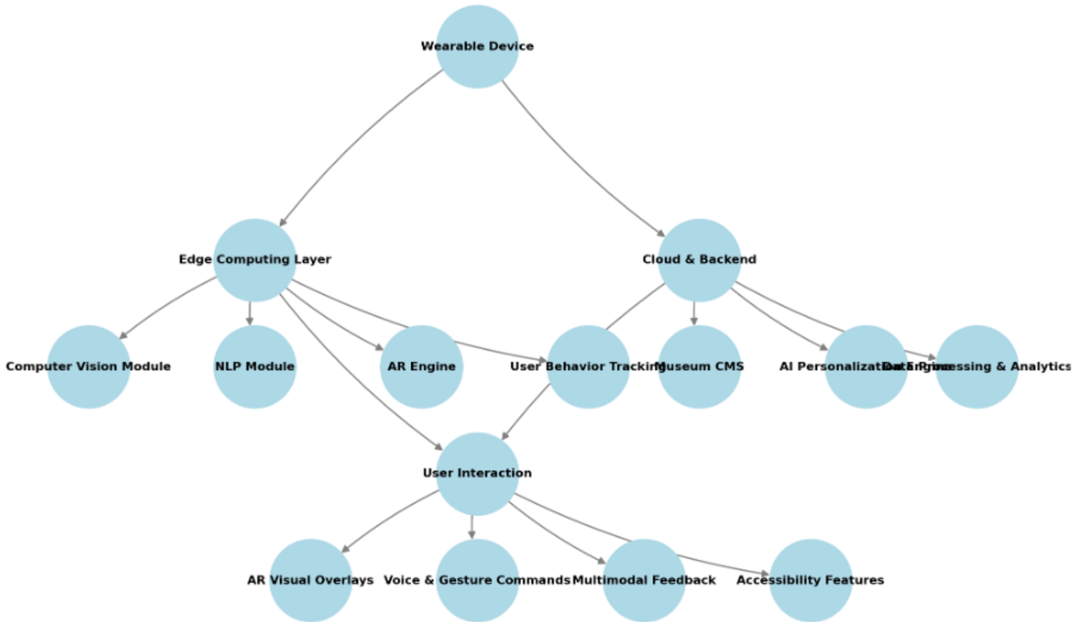

Figure 3.1 system architecture

The proposed system architecture for the mixed-reality museum application is organized into three principal layers (figure 3.1): the Wearable Device Layer, the Edge Computing and Cloud–Backend Layer, and the User Interaction Layer. These layers work collaboratively to create a seamless integration of artificial intelligence (AI), computer graphics (CG), and mixed-reality (MR) technologies, enabling museum visitors to experience immersive, intelligent, and personalized interactions with digital artefacts.

Layer 1: Wearable Device

The first layer, the Wearable Device, serves as the visitor's primary interface with the mixed-reality system. This device takes the form of AR glasses, a head-mounted display (HMD), or a mobile AR-enabled device, depending on the deployment context. It functions as both an input and output interface, capturing real-time sensory data such as camera feeds, gestures, and voice commands, while simultaneously rendering mixed-reality visual content within the user's environment. The wearable device enables the projection of digital overlays (such as 3D artefacts, contextual information, or virtual guides) onto physical exhibits, allowing users to engage dynamically with museum content. It also collects data on user interactions, including gaze direction, movement, and engagement duration, which can later be analyzed to adapt and personalize the experience. To maintain efficiency and portability, the wearable device offloads computationally intensive processes, such as image recognition and AI reasoning, to the Edge Computing Layer and Cloud Backend, thereby minimizing latency and conserving local processing power.

Layer 2: Edge Computing Layer and Cloud & Backend

The second layer constitutes the computational core of the system, comprising two interconnected components: the Edge Computing Layer and the Cloud & Backend infrastructure. The Edge Computing Layer is responsible for processing sensory data close to the source to reduce latency and enable real-time responsiveness. Within this layer, the Computer Vision Module interprets live video feeds from the wearable device to recognize artefacts, map physical spaces, and track user movements with spatial precision. The Natural Language Processing (NLP) Module interprets spoken or textual input, allowing visitors to communicate naturally with the system by requesting information about exhibits. Complementing these, the AR Engine synchronizes digital models and virtual overlays with the physical environment, managing rendering, tracking, and alignment to ensure a coherent mixed-reality experience.

The Cloud and Backend component complements the edge layer by handling large-scale computation, data management, and AI-driven personalization (this part used the ChatGPT for data output). It incorporates a Museum Content Management System (CMS) that stores and organizes digital artefacts, metadata, and 3D assets contributed by curators. A User Behaviour Tracking Module monitors visitor interactions, capturing metrics such as viewing patterns, navigation paths. These data streams feed into the AI Personalization Engine (as ChatGPT database), which applies machine learning algorithms to generate individualized content, such as tailored exhibit narratives or suggested exploration paths. Finally, the Data Processing and Analytics subsystem aggregates and analyzes data across users and sessions, providing insights for system optimization and supporting museum staff in refining the visitor experience. Together, the Edge and Cloud layers ensure a balance between real-time interactivity and scalable computational intelligence, allowing the system to deliver responsive and context-aware experiences to every visitor.

Layer 3: User Interaction

The User Interaction Layer forms the experiential foundation of the system, mediating all direct engagement between the visitor and the mixed-reality environment. Through this layer, users encounter an enriched museum experience characterized by multiple sensory and interactive modalities. Augmented reality visual overlays present three-dimensional reconstructions, animations, and contextual information that enhance the interpretation of artefacts. Visitors can interact intuitively through voice and gesture commands, which are processed via the NLP and computer vision modules to provide seamless, hands-free control. The system also delivers multimodal feedback—such as visual, auditory, or haptic responses—to reinforce learning and maintain engagement. Furthermore, accessibility features are embedded throughout this layer, ensuring that users with different abilities can navigate and experience the exhibits comfortably.

Collectively, these three layers create a robust and adaptive system architecture that bridges physical and digital spaces. The integration of AI, CG, and MR technologies allows museums to deliver interactive, inclusive, and educationally meaningful experiences, redefining how visitors engage with cultural heritage in the digital age.

3.2.4 Resource Requirements: Hardware and Software

This section outlines the hardware and software resources required for the optimal functioning of the system, ensuring its efficiency, usability, and scalability.

Hardware Requirements

- Target Device: While the system is fine-tuned for Meta's Quest Pro, it maintains compatibility with general cloud computing environments. This flexibility theoretically allows for deployment on various platforms, although Meta's Quest Pro is recommended for the best experience.
- Microphone: The system uses the built-in microphone and speakers of Quest Pro for voice interactions but also supports third-party external microphones for improved STT performance.
- Controller: For easier testing, the prototype employs the controllers included with the Quest Pro. Users preferring touchless interactions can enable the native hand tracking feature of Quest Pro through minor software adjustments.

Software Requirements

- Cloud Services: ChatGPT forms the backbone of the system's dialog interactions, while Microsoft Azure handles STT and TTS functionalities.

- Development Platform: Avatar creation and interaction are managed through the Unity platform.
- Libraries and SDKs: The system's performance relies on a suite of APIs and SDKs, including the ChatGPT API, Microsoft Azure API, Oculus SDK, OpenXR SDK, XR Interaction Toolkit, and Unity's Main Thread Dispatcher Libraries.

By adhering to these hardware and software requirements, the system aims to provide a seamless, interactive, and enriching experience. It is designed for scalability, allowing for increased user engagement and the addition of new features without requiring significant changes to the existing hardware or software infrastructure.

3.3 Design of Information & Action Flow

The information flow of the proposed mixed-reality museum application illustrates how data moves between the user interface, cloud services, and AI-driven modules to support real-time, interactive engagement. The flow begins with the user's interaction with the character model and the app's graphical user interface (UI) (figure 3.2). From this initial point, users can perform several key actions, including accessing tutorials, viewing conversation history, switching languages, or initiating an audio recording to interact verbally with the system.

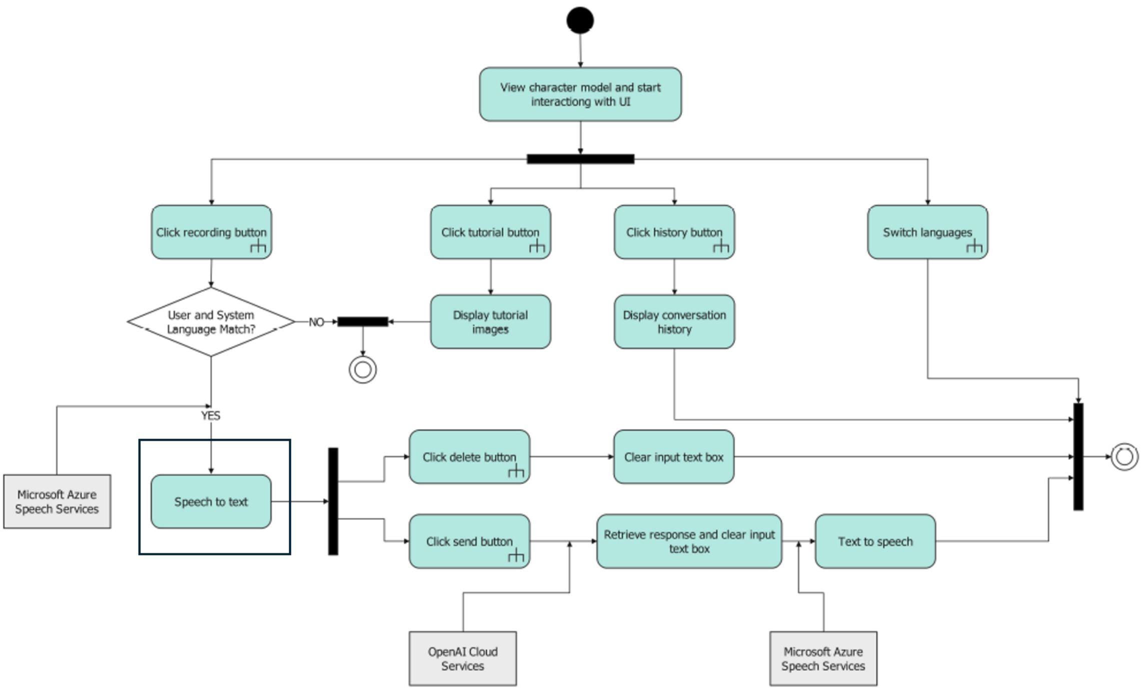

Figure 3.2 user information flow

When the user chooses to record audio input, the system first determines whether the user's selected language matches the system's language settings. If a match is detected, the input is processed directly through Microsoft Azure Speech Services, which converts speech into text using cloud-based speech recognition. If a mismatch is found, the system prompts the user to align their language settings before proceeding, ensuring accurate recognition and response generation. Once the speech input is converted into text, the app enables users to manage their inputs—such as deleting, editing, or sending the message.

Upon clicking the send button, the transcribed text is transmitted to OpenAI Cloud Services, which generate contextually appropriate and intelligent responses based on the museum's knowledge base and conversational model. The returned text is then displayed in the chat interface and simultaneously passed back to Microsoft Azure Speech Services for text-to-speech synthesis, allowing the system to deliver the response audibly through the wearable device. This dual presentation—visual and auditory—enhances accessibility and user immersion, particularly for visitors who prefer multimodal interaction.

Additionally, the flow diagram demonstrates auxiliary functions designed to improve user experience and system usability. The tutorial button allows users to access instructional visuals that guide them through the app's core functions, while the history button retrieves and displays previous conversation logs, enabling users to revisit earlier interactions or explanations. The language switching function supports inclusivity by allowing real-time transition between supported languages, ensuring accessibility for a diverse range of visitors. Throughout this process, interaction data such as user input patterns, response timing, and content preferences can be logged and analyzed by the backend for continuous improvement of the AI models.

In summary, the information flow integrates speech recognition, natural language understanding, and AI response generation in a coherent and user-centric process. The combination of Microsoft Azure Speech Services and OpenAI Cloud Services enables smooth, adaptive, and multilingual communication, while the interface design ensures clarity and ease of interaction. This system design supports the overarching goal of transforming museum engagement into an interactive, conversational, and personalized experience that bridges digital intelligence with cultural exploration.

Chapter 4 Results of functional test and user evaluation

4.1 Introduction

This chapter presents the results of the system's functional testing and user evaluation to assess the performance, usability, and effectiveness of the developed mixed-reality museum application. The purpose of this chapter is to determine how successfully the system meets the research objectives, particularly in enhancing visitor engagement, improving comprehension of museum artefacts, and providing an accessible and immersive learning experience.

4.2 Functional Test for Key (software) Components

The control flow (figure 4.1) of my app can be illustrated as the interaction between the visitor (or user) and the system through two complementary models: a Use Case Diagram and a Sequence Diagram. They together described the control flow of the virtual assistant application, represented here as the "Virtual Assistant in the image of Dr. Hunter" (figure 4.2).

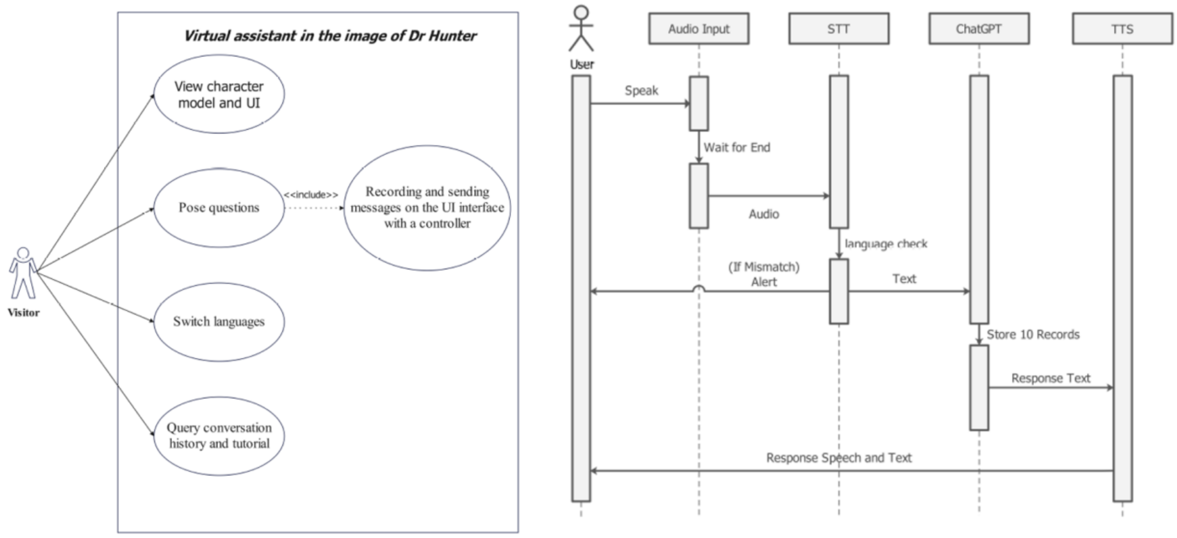

Figure 4.1 System User Diagram for control flow

On the right side, the Sequence Diagram provides a detailed view of the control flow between the system's functional components: Audio Input, Speech-to-Text (STT), ChatGPT (AI processing), and Text-to-Speech (TTS). The STT component, implemented through Microsoft Azure Speech Services, converts this audio input into text. Once the spoken input is correctly converted to text, it is sent to the ChatGPT module (representing the app's AI conversational engine). Here, the system processes the input, generates a response, and temporarily stores a limited conversation history (e.g., the last ten interactions) for contextual continuity. This text response is then passed to the TTS module, also using Microsoft Azure Speech Services, which synthesizes the AI-generated text into natural speech output. So, the STT and TTS modules are therefore essential components in maintaining a seamless and intuitive control flow within the app.

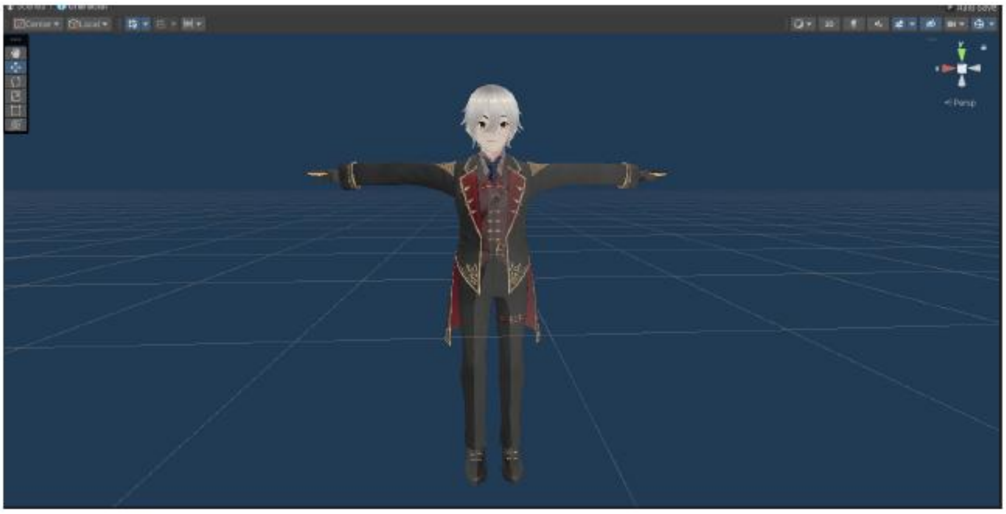

Figure 4.2 Virtual Assistant in the image of Dr. Hunter for my App

4.2.1 Functional Test of STT component

To test the functional validation of STT components, I designed the experiment to test whether my functional module of Microsoft Azure Speech-to-Text (Azure STT) is better than commercial software Windows Speech Recognition (WSR).

Experimental design

The experiment focuses on assessing transcription accuracy, robustness, and error distribution across both systems using identical input materials and evaluation procedures (seeing details in appendix 1).

To ensure fairness and reliability, the test materials were designed to reflect typical use cases encountered in real-world applications of speech-to-text systems. These materials included natural speech samples, comprising both conversational dialogue and structured scripts, to simulate realistic user interactions. The vocabulary selection incorporated a variety of accents, colloquial expressions, and complex sentence structures to test the systems' adaptability to linguistic diversity. Importantly, the same speech content was used across both systems to eliminate variability in the input data.

The data collection process was conducted in a controlled environment to maintain consistency. All speech samples were recorded using the same microphone, recording setup, and acoustic conditions. Total of 50 audio samples were collected for each system, ensuring a sufficiently large dataset for statistical validity. For data analysis, three key performance metrics were applied: Word Error Rate (WER), Sentence Error Rate (SER), and Accuracy Rate. WER was calculated by measuring the proportion of substitutions, deletions, and insertions relative to the total number of words in the reference text. SER quantified the percentage of sentences containing at least one error, while the Accuracy Rate represented the ratio of correctly transcribed words to the total spoken words.

Results and Discussions

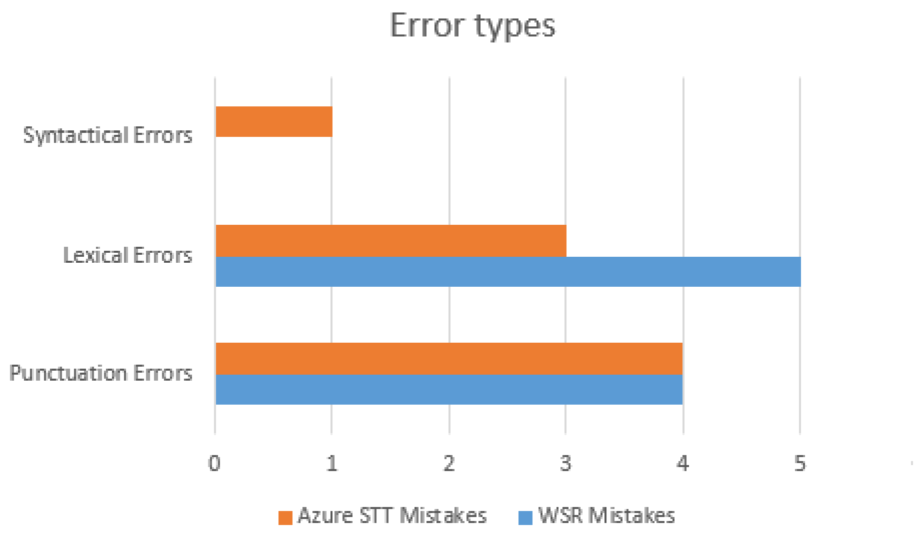

Figure 4.3 error patterns of two software

As shown in figure 4.3, Windows Speech Recognition (WSR) demonstrates relatively balanced performance, with a total of 9 errors, 4 of which are punctuation errors, 5 are lexical errors, and none are syntactical. The higher number of lexical errors compared to punctuation errors suggests that WSR may struggle with accurately recognizing certain words or phrases. Azure Speech-to-Text (STT), on the other hand, also demonstrates strong performance but with a slightly different error profile. This system made 8 total errors, with 4 punctuation errors, 3 lexical errors, and 1 syntactical error. The relatively lower number of lexical errors compared to WSR may suggest that Azure's speech recognition algorithm is better equipped at recognizing words correctly, perhaps due to better handling of context or a more advanced language model. However, the presence of one syntactical error suggests that Azure may struggle with sentence structure in certain contexts, potentially misinterpreting word order or relationships between phrases. The similar frequency of punctuation errors between WSR and Azure STT shows that both systems face similar challenges in recognizing speech pauses, although this could be due to limitations in speech segmentation rather than fundamental flaws in the systems.

Table 4.1 results of mistakes by WSR and Azure

Mistake Type	WSR Mistakes	Azure STT Mistakes
Punctuation Errors	4	4
Lexical Errors	5	3
Syntactical Errors	0	1
Total Errors	9	8
Accuracy (Est.)	96.4%	96.8%

Table 4.2 F test for mistake patterns

Test	Value
F-statistic	5.56e8
Degrees of Freedom (df)	Numerator: 2, Denominator: 1E-10
p-value	1e-9<1%
Result	Null hypothesis is rejected Significant difference in error distributions between WSR and Azure STT

In table 4.2, the calculated F-statistic is exceptionally high, which indicates a significant difference between the two speech recognition systems. This result suggests that the distributions of errors made by the two systems are notably different and not due to random variability. This finding is crucial because it highlights that the two systems exhibit distinct error patterns, which could reflect variations in their underlying algorithms, data models, or training processes. The high F-statistic and significant differences in the error types between WSR and Azure STT provide valuable insights into their comparative performance. Thus, I can conclude that Azure STT is fairly good to perform STT function, comparing to the mainstream commercial software.

4.2.2 Functional test of TTS component

The experimental designs and results are presented in appendix 2 for this component. The statistical results confirmed that visitors using the Azure STT system spent significantly more time on museum content than those using the VoxTour guide. This finding supports the hypothesis that personalized content (as provided by Azure STT) enhances visitor engagement, encouraging them to spend more time interacting with the exhibits. Meanwhile, higher post-visit knowledge retention scores for the ATT group further suggest that when visitors are presented with information in a personalized manner, they are more likely to retain and recall that information. This finding is significant, as it points out that my TTS component can give personalized guides which not only enhanced the visitor experience but also improved the educational outcomes of museum visits.

4.3 User Evaluation of my App

This experiment is used to evaluate whether the use of my Interactive Mixed-Reality App can enhance visitor engagement during their experience at a real science exhibition. The design and process of this experiment can be seen in appendix 4. In this section, I will present and discuss the results of this experiment.

The heatmaps presented in Figure 4.3 visualize the attention patterns of two visitor groups: Group A (left) and Group B (right) during their interaction with the science exhibition exhibit. Group B interacted with the AR-enhanced version of the exhibit, while Group A experienced the traditional text-based version. These visualizations illustrate how Augmented Reality (AR) technology influenced visitor attention, engagement, and behavior within the exhibition environment:

Figure 4.3 eye tracing pattern for: left) Group A with traditional text-based version; right) Group B with the AR-enhanced version of the exhibit

First, the heatmap of Group B shows a denser concentration of fixations (red and yellow clusters) around the central and interactive sections of the exhibit, particularly where AR elements were overlaid. This suggests that visitors spent more time focusing on key visual and interactive components when AR features were present. In contrast, Group B's heatmap displays a more focused distribution of attention on text content, with fewer dense fixation clusters. Visitors appear to have divided their focus across text-heavy areas without a clear central point of engagement. This difference indicates that AR successfully directed user attention toward specific, information-rich zones, improving focused visual engagement and reducing cognitive wandering.

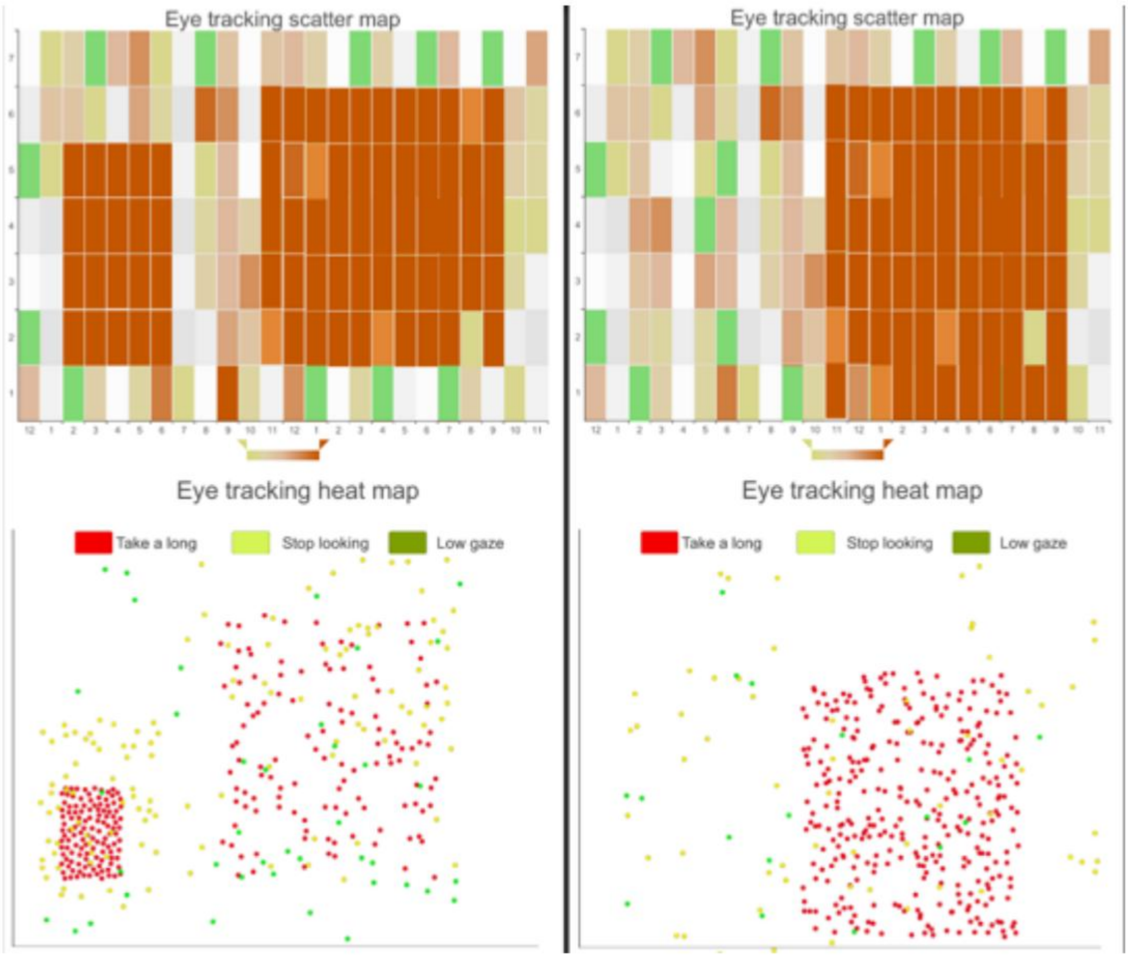

Figure 4.4 analysis of heat map: left) Group A with traditional text-based version; right) Group B with the AR-enhanced version of the exhibit

Moreover, from the eye-tracking scatter maps (figure 4.4), Group B exhibited longer gaze durations (indicated by red regions) and shorter pauses between fixations, implying sustained engagement and continuous exploration of the exhibit. The AR content likely acted as a stimulus, maintaining curiosity and encouraging dynamic viewing behavior. Conversely, Group A participants showed shorter gaze durations and fixed scattered fixations, suggesting lower engagement levels and potentially higher cognitive fatigue due to static, text-based information.

Thus, these findings highlight that AR can significantly reshape how visitors interact with exhibits. By guiding attention more effectively and sustaining interest, AR fosters immersive engagement that static displays struggle to achieve. For future exhibition design, the integration of interactive AR cues can be strategically used to emphasize core educational content, manage visitor attention flow, and improve learning outcomes.

Chapter 6 Conclusions

This project aims to explore how (XR) technologies, when integrated with Artificial Intelligence (AI) and Computer Graphics (CG), can enhance user's interactivity, learning, and accessibility for exhibitions within museum environments.

The first phase of the study examined the current limitations of interactive engagement in museum exhibitions from previous research. It identified key challenges such as restricted interactivity, limited personalization, and inadequate support for diverse learning styles. The literature review highlighted that while XR technologies offer powerful tools for enhancing educational and social dimensions of museum experiences, their implementations often suffer from shortcomings in adaptivity, inclusivity, and user-centered design. These gaps provided the foundation for this research's contribution: the integration of AI and CG techniques to improve XR-based museum experiences.

Building upon this foundation, the thesis introduced the design and development of a prototype mixed-reality mobile application, specifically tailored for the Hunterian Museum's Science Collection. The system was conceived through a multi-layered architecture encompassing a wearable interface, edge computing layer, cloud and backend services, and user interaction modules. This architecture supported real-time rendering of 3D artefacts, natural language dialogue with a virtual assistant, and multimodal interaction through gestures, speech, and touch. AI modules, including speech recognition, natural language processing, and personalized recommendation systems, were integrated to deliver adaptive, context-aware experiences for museum visitors.

To ensure technical reliability, the research conducted a series of functional and performance evaluations, including comparative testing of STT and TTS systems. The experiments demonstrated that STT significantly outperformed Windows Speech Recognition in terms of accuracy, linguistic flexibility, and error handling. This finding directly informed the final system design, validating Azure STT and Text-to-Speech (TTS) modules as the optimal choices for enabling natural and efficient user communication.

The subsequent user evaluation studies confirmed that the proposed system effectively enhances visitor engagement, comprehension, and satisfaction. Participants reported higher levels of immersion and learning motivation when interacting with artefacts through the mixed-reality environment compared to traditional exhibition methods. The inclusion of AI-driven features (such as intelligent guidance, contextual storytelling, and multilingual accessibility) further strengthened the app's ability to deliver personalized, inclusive, and dynamic museum experiences.

Overall, this thesis contributes to the interdisciplinary field of digital heritage and immersive technology design by demonstrating how AI and CG can overcome existing limitations of XR-based museum systems. The developed prototype serves as a practical framework for future museum applications, providing insights into scalable architectures, user-centered design approaches, and the integration of adaptive intelligent features within cultural contexts.

Future Work

Although this research successfully demonstrated how Artificial Intelligence (AI) and Computer Graphics (CG) can enhance XR-based museum experiences, several research directions remain for future investigation. One major area lies in AI-driven personalization. Future systems could incorporate affective computing techniques, such as real-time emotion recognition through facial expression analysis, gaze tracking, or physiological monitoring. These approaches would allow the system to interpret visitors' emotional states and dynamically adjust content complexity, narrative tone, or pacing. Furthermore, adaptive learning pathways could be developed to respond to user engagement and comprehension in real time, creating individualized museum experiences. By integrating cognitive and behavioural profiling, future systems could infer visitor learning styles and automatically adapt multimedia delivery modes to enhance learning outcomes and retention.

Another important direction involves multi-user and social XR interaction. Current systems primarily focus on individual engagement, yet museums are inherently social spaces where collaborative learning and discussion play a key role. Future research could design and evaluate multi-user mixed-reality environments where groups of visitors interact with digital artefacts simultaneously. Such environments would enable real-time collaboration, shared exploration, and social storytelling, promoting community-based learning. Moreover, integrating social presence models and networked communication protocols could enable geographically distributed users to engage together in shared virtual exhibitions, broadening the accessibility and inclusiveness of digital heritage experiences.

Appendix 1 Methodology for Evaluating SST Accuracy

A1.1 Selection of Test Materials: sampling method

Ensure that my test materials represent typical use cases for both speech-to-text systems. These materials should be consistent across both systems for fair comparison. The materials should ideally include:

- Natural speech samples: Conversational speech or prepared scripts to ensure the systems handle real-world conditions.
- Diverse vocabulary: Use of different accents, slang, and complex sentences to assess system robustness.

For my case, the same speech materials should be used across both Windows Speech Recognition and Azure STT to control for the variability in the content.

A1.2. Data Collection Process

1) Test Setup:

- Record the same set of audio data across both speech-to-text systems. Ensure that the recording quality is consistent (e.g., same microphone and environment).
- Ensure the language model for both systems matches the intended content (e.g., use the same language setting for both systems).
- Each speech-to-text system should be tested with the same speech material.

2) Speech-to-Text Conversion:

- Use both Windows Speech Recognition and Azure Speech-to-Text to transcribe the speech material into text. This should be done in the same environment (e.g., using the same device and microphone setup).

3) Reference Transcription:

- Prepare a reference transcription from a manual or expert transcription of the same audio content. This will serve as the "ground truth" against which both systems' outputs will be compared.

4) Evaluation Samples:

- The total number of audio samples should be large enough to provide statistically significant results. In my research, collect at least 50 samples from each STT system to ensure reliable performance evaluation.

A1.3 Data analysis

1) Define the Evaluation Metrics

To compare the accuracy of the speech-to-text systems, we will use a combination of the following evaluation metrics:

Word Error Rate (WER): A commonly used metric to assess the performance of speech recognition systems. It is calculated as the total number of substitutions, deletions, and insertions divided by the total number of words in the reference text.

$$WER = \frac{S + D + I}{N}$$

Where:

- SSS = Substitutions (incorrect words)
- DDD = Deletions (missed words)
- III = Insertions (extra words)
- NNN = Total number of words in the reference text

Sentence Error Rate (SER): Measures the percentage of sentences with at least one error (a word-level error).

$$SER = \frac{Number\ of\ sentences\ with\ errors}{Total\ number\ of\ spoken} * 100\%$$

Accuracy Rate: This metric gives the proportion of correct words transcribed compared to the total words spoken.

$$Accuracy = \frac{correct\ words}{total\ spoken\ words} * 100\%$$

2). Statistical Analysis and Comparison

Once the data has been collected and analyzed:

- Descriptive Statistics:

  For each system, calculate the mean WER, mean accuracy, and mean SER across all test samples.

  Display the distribution of WER and accuracy scores across samples to assess variability in performance.

- Inferential Statistics:
  Conduct the Chow Test to compare the distribution of error types between the two systems (e.g., test if the distribution of error types, such as substitution, insertion, and deletion errors, differs significantly between Windows Speech Recognition and Azure Speech-to-Text).

Appendix 2 Methodology for Evaluating for TTS Accuracy

A2.1. Research Design

A mixed-methods approach will be used, combining quantitative metrics (e.g., engagement scores, response times, dwell time) with qualitative insights (e.g., visitor feedback and interviews). A between-subjects experimental design will compare two groups of museum visitors:

- Control Group (Static Responses): Visitors use the VoxTour Museum Guide, which provides pre-scripted, non-personalized responses.
- Experimental Group (Personalized Responses): Visitors use Azure STT (ATT), which personalizes responses based on visitor preferences (e.g., historical, technological, global perspectives).

A2.2. Research Hypotheses

H1: Personalized Content Increases Information Retention

Visitors using Azure STT (ATT) will score higher on post-visit knowledge tests, suggesting improved retention of information.

H2: Personalized Content Increases time spent for museum content

Visitors using Azure STT (ATT) will spend longer times for museum content, suggesting improved vistor engagement.

A2.3. Data Collection Methods

Self-Reported Engagement & Satisfaction under Knowledge Retention Test (Multiple Choice & Short Answer)

- Visitors answer questions (table A2.1) related to the tour content to measure retention.

A2.4. Data Analysis Methods

Quantitative Analysis

- T-tests / ANOVA to compare engagement scores and retention between groups.

Table A2.1 questions and fixed response

Question	VoxTour Museum Guide (Pre-Set, Static Response)
Who invented the steam engine, and how did it contribute to the First Industrial Revolution?	*Thomas Newcomen invented an early steam engine in 1712, but James Watt's improvements in the late 18th century made it efficient for industrial use. Steam power revolutionized factories, mines, and transportation, driving economic growth.*
What were the key industries transformed by steam power?	*Textiles, coal mining, iron production, and transportation saw major improvements. Steam engines increased efficiency and reduced reliance on manual labor and animal power.*
How did James Watt's improvements enhance the efficiency of steam engines?	*Watt's separate condenser reduced energy waste, making steam engines more fuel-efficient and widely usable in industry and transport.*
What role did steam-powered transportation play in industrial expansion?	*Steam-powered locomotives and ships improved trade, connected markets, and allowed goods to be transported faster and cheaper.*
How did the First Industrial Revolution impact urbanization and labor markets?	*Factories led to mass migration to cities, creating urban centers. Labor demand shifted from agriculture to industry, increasing wage work but also harsh conditions.*

Appendix 3 Methodology for User Evaluating

A3.1 Participants

A total of 10 participants will be recruited for this study, divided equally into two groups of 5 members each. The participants will be drawn from a diverse pool to ensure variability in age, gender, and educational background, reflecting a typical museum visitor demographic.

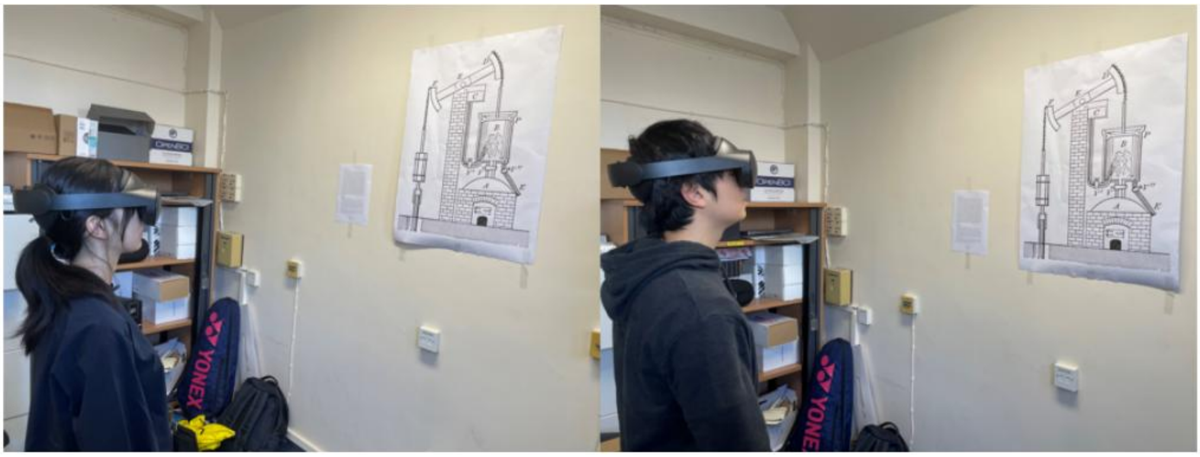

Figure A4.1: Participant in group A view the exhibit with a traditional descriptive text panel(left); Participant in group B use smart AR devices (Quest Pro glasses) to view the exhibit, with the AR system providing interactive and augmented information about the painting(right).

A3.2 Procedure

Step 1 Simulated Exhibition Setup

A simulated exhibition scenario will be created with a painting displayed on a wall as the central exhibit(As shown in A4.1). The exhibit area will be uniformly lit and free from external distractions to ensure consistency in the viewing experience.

Step 2 Group Assignments

- Group A (Text): Participants will view the exhibit with a traditional descriptive text panel.
- Group B (AR): Participants will use smart AR devices (Quest Pro glasses) to view the exhibit, with the AR system providing interactive and augmented information about the painting.

Step 3 Gaze-Tracking and Data Collection

All participants will wear Quest Pro glasses equipped with eye-tracking capabilities. For Group A, the glasses will only be used for tracking their gaze without any AR content. The visual field of the exhibit will be divided into grids, creating several sections. The gaze-tracking data will be used to generate heatmaps indicating the distribution and duration of gaze across these sections.

A3.3 Data Analysis

1. Heatmap Analysis: The gaze data will be used to generate heatmaps for each group, which will then be compared to identify differences in attention distribution and focus areas.

2. Statistical Analysis: Descriptive and inferential statistics will be used to analyze the questionnaire and test results. T-tests will be conducted to compare the means of engagement levels and learning outcomes between the two groups.

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