IMPULSE

IMmersive digitisation: uPcycling cULtural heritage towards new reviving StratEgies

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Report on the review of the latest MUVE technologies, processes, formats, best practices, impediments.

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Abstract

In line with the aims of WP2 of the IMPULSE project, this report highlights the current technological landscape for the purpose of facilitating the development of decentralised, open-access solutions for reusing, recycling, and / or upcycling existing digitised cultural heritage content in a way that will bolster user engagement via the adoption of novel eXtended Reality (XR) technologies by cultural institutions.

The second chapter of the document revolves around the concept of interconnected multi-user virtual worlds that constitute the Metaverse. It examines the transition from existing standards and practices towards what may be named 'Web 4.0', a new landscape that incorporates virtual worlds in ways that reinforce interoperability and reflect the values and principles of the European Union. This delineation of current and projected future trends is important for the requirements analysis of the system to be developed in the context of WP2.

The third chapter presents a number of indicative case studies of multi-user VR for the presentation of cultural heritage content. Limitations that are present in traditional interaction methods are identified and ways of reducing their impact via the adoption of novel interaction paradigms are highlighted. Selected case studies, including the ones designed and developed with the participation of project partners, are analysed in greater detail in order to illustrate the opportunities that arise through the use of environmental storytelling in multi-user virtual worlds that feature cultural heritage content. The chapter ends with an analysis of the above-mentioned case studies according to an extensive list of criteria, by which multi-user virtual environments for cultural heritage may be presented, described, and analysed. These criteria are identified to be in line with the aims and objectives of IMPULSE.

The following chapter examines the design trends and the interaction modalities that enhance the User Experience of social VR interfaces; communication methods and technological aspects that underpin effective social VR experiences are also examined in this context. The chapter in question highlights the tendency of providing means of incorporating nonverbal communication into the intended use of social VR platforms through the use of Head Mounted Displays, motion controllers, immersive auditory setups, face, hand and body tracking, motion capture, and other advanced interaction methods (e.g. Brain-Computer Interaction).

In the next chapter, existing content aggregators are examined in light of the objectives of WP2 and the IMPULSE project as a whole. An exploratory research into open databases for cultural heritage identifies the advantages and limitations of current databases. Key findings reveal significant challenges in the digital cultural heritage ecosystem, including repository fragmentation, heterogeneous metadata standards, and varying degrees

of data accessibility (and therefore discoverability). Furthermore, the APIs of Sketchfab and Europeana are examined in greater detail, concluding that their integration into IMPULSE's pilots would be possible but would require custom development in order to overcome the differences of these two platforms in terms of data structures and content types.

Following up from the preceding chapter, a detailed overview of the state of the art of current software solutions for the development of social VR applications and multi-user virtual environments is provided. This review leads to the identification of two main categories, reflecting respective creative approaches: (i) online, proprietary platforms available as services and (ii) development platforms, tools and components for in-house application implementation. The benefits and drawbacks of each option are then identified, along certain key axes pertaining to the IMPULSE project, the concept of the Metaverse for Cultural Heritage, education and artistic creation, while taking into account the current availability of numerous development aids. This investigation leads to a preliminary recommendation according to which the in-house development of a low TRL platform via the IMPULSE project, is an appealing option.

The concluding chapter of this report highlights a number of insights gained through the investigation of the current technological landscape, as detailed in the preceding chapters: (i) a preference for visual fidelity over designing and implementing effective and efficient collaboration among users, (ii) comparatively low user interactivity with the featured content (as complex editing remains elusive), which prevents large-scale citizen involvement in the preservation and (re)interpretation of cultural heritage content, (iii) a predominance of custom-made solutions for specific projects, (iv) an increased tendency to incorporate more natural and intuitive interaction modalities for user communication in the context of social VR, and (v) the need for standardisation across cultural heritage content repositories, databases, and platforms**.**

Key words: Cultural Heritage, Virtual Reality, eXtended Reality, Social Virtual Reality, Multi-user Virtual Environments, Virtual Worlds, Metaverse, API, Embodied and Multimodal Interaction, Content Aggregators.

Abbreviations and Acronyms

Abbreviation / acronym	Description
DX.X	Deliverable number X belonging to WP X
EC	European Commission
WP	Work Package
CH	Cultural Heritage
3D	Three-dimensional
VE	Virtual Environment
VR	Virtual Reality
XR	eXtended Reality
MUVE	Multi-User Virtual Environments
CVEs	Collaborative Virtual Environments
VWs	Virtual Worlds
IVWPs	integrated virtual world platforms
API	Application Programming Interface
DDL	Direct Download

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1 Introduction

The WP2 of the IMPULSE project aims to identify technological approaches which can support the re-use of digitised Cultural Heritage content by Cultural Heritage Institutions in order to allow for further audience engagement, with the adoption of novel eXtended Reality (XR) technologies. The IMPULSE project and consequently WP2 too will focus specifically on Metaverse platforms and related technologies as contexts for re-use and presentation.

In order to clarify the technological environment that IMPULSE focuses on, it is important to briefly define the term Metaverse: a web-based, persistent, simulated 3D graphical environment, providing multiple users with avatars and communication tools with which to act and interact in-world and in real-time, via immersive or other forms of interfaces (mixed or extended reality). More detailed definitions and references will be provided in the next chapter.

After taking into account the above, the WP's main objectives are to investigate relevant technological solutions in order to provide recommendations towards creating a sustainable, decentralised, open access solution, which will support the reuse / recycling / upcycling of already existing digitised Cultural Heritage content by Cultural Heritage Institutions, allow for further audience engagement, with the adoption of novel XR technologies and provide future policies that can be adopted by Cultural Heritage Institutions.

According to the IMPULSE project's objectives and structure, Task 2.1 titled "Research on barriers and opportunities to re-usage of CH content in the Metaverse" will investigate existing technological solutions supporting development of multi-user virtual environments, as well as case studies of developed virtual environments as contexts for the presentation of CH content of various types and forms (3D models, text, images, video, audio recordings[1]). More specifically, this task will investigate:

- existing technological solutions for presenting digitised Cultural Heritage content in the context of multi-user virtual environments
- case studies of project implementations, utilising virtual environments as contexts for the presentation of CH content of various types.

In order to achieve these objectives, a review of the state-of-the-art-technology that may support the presentation of CH content in the Metaverse will be provided, including

[1] In accordance with the data classification adopted in WP3, we could suggest that content to be presented in these CH virtual environments may include: 2D (images, text), 3D (3D models) or 4D (video, audio recordings) data.

existing technological tools, platforms and applications. Both proprietary and open-source platforms related to the Metaverse, will be compared in order to identify appropriate solutions to support the specific objectives of the project. The above activities will be undertaken in order to identify the advantages and disadvantages of the different technological solutions available for creating and supporting multi-user virtual environments while taking into account the overall aims and objectives of the project. Additionally, the possibility of integrating IMPULSE with existing content aggregators (Europeana, Wikidata, SketchFab, etc.) will be investigated.

Additionally, previous initiatives of using Multi-User Virtual Environments for presenting CH content, will be investigated for the purpose of identifying the pros and cons of these approaches, the best practices that we can learn from, successful solutions, and drawbacks. This effort will aim at gaining an understanding of the purposes, adopted perspectives and methodological principles of the initiatives within which previous technological solutions have emerged, in order to discover issues that need to be addressed and provide a new technological context wherein new forms of presentation of existing digitised content may be hosted. Through desk research of existing platforms, projects and products, a selected number of technological solutions as well as implemented cases will be identified for further in-depth research.

Following the completion of Task 2.1, interaction with activities of WP1, WP3 and WP4 will continue in order to reach a conclusion regarding the most appropriate technological and methodological approach by taking into account the results of certain tasks in these WPs too. During the next phases of WP2, a platform supporting the development of multi-user virtual environments (metaverse / virtual worlds) will be created and will be effectively utilised by the research teams in WP1 in order to support their activities: conduct artistic research (1.2) and research on the re-use of CH content via participatory processes by students and educators in participating Universities. Additionally, online and offline activities such as hackathons and/or workshops with stakeholders will be organised in order to further discuss and evaluate the technological and methodological approach that has been previously identified. Furthermore, in order to explore the possibility of integrating IMPULSE with existing content aggregators, partners will explore how their respective API development processes relates to the IMPULSE platform development architecture and processes, as well as to the European Collaborative Cloud for Cultural Heritage initiative.

2 Definition of the Metaverse, Virtual Worlds & Multi-User Virtual Environments

2.1 The evolution of Social Virtual Reality (VR)

Research and development in the area of virtual worlds commenced during the early 90s, at the confluence of the fields of VR technologies, Networked and Distributed Computing and Computer Supported Collaborative Work (Snowdon, Churchill & Munro, 2001). The first systems that supported multi-user interaction in virtual environments were DIS, DIVE, MASSIVE (Greenhalgh & Benford, 1995), etc. The first commercial web-based system, which supported synchronous multi-user interaction for remotely placed individuals and emphasised its social functionality was Alpha World (later known as Active Worlds), created in 1995. In the same year, Blaxxun Interactive started developing several 3D browsers, using the VRML language and shortly after, it acquired Cybertown (Kaneva, 2007), one of the first commercially successful online communities enabling chat within a 3D environment. Since then, several other examples of such systems have emerged over the years, integrating increasingly realistic and elaborate forms of representation, in props and avatars as well as real-time voice communication along with text-based communication (i.e. There, AltSpaceVR, Second Life, etc.).

The idea of virtual worlds can be said to have entered the public consciousness around 2007 as a result of the increasing popularity of Second Life, the most well-known and successful virtual world to date. Second Life is a heavily "populated", vast and complex multi-user virtual environment, that has revealed the creative, cultural, economic, and social potential that such globalised virtual communities may have and one that has been explored by numerous mostly qualitative and ethnographic studies (Minocha & Reeves, 2010; Kaplan & Haenlein, 2009; Meadows, 2008; Boellstorff, 2008).

The types of second generation VR systems – which can be accessed via desktop computers, tablets, smartphones, and head-mounted displays - fall into two main categories: Collaborative Virtual Environments (CVEs) and Massively Multiplayer Online Games (MMOGs or MMO for short) (Tromp et al, 2018, 132), however, as Tromp et al explain "social VR systems can also simply be [...] a space to meet and talk, or collaborate on a building or viewing shared virtual 3D objects in the virtual world" (2018, 132)

The literature documenting research on virtual worlds is extensive, including studies by Schroeder (1996 and 2002), Biocca and Levy (1995), Boellstorff (2008), Marini (2012) and others. However, the web-based virtual worlds investigated in these studies mostly afforded non-immersive modes of social interaction amongst users and supported a very limited selection of 2D input devices for navigation and object manipulation. Additionally, they had several significant features that differentiated them from social media, namely real time interaction, avatar personification and the fact that action took place within a 3D environmental context (Kaplan & Haenlein, 2009 p. 566). The new generation of VR hardware developed since the emergence of the Oculus Rift in 2013 has signalled a new phase of development for VR technological infrastructure, both in terms of hardware and software. Major improvements on the quality and performance of VR hardware and the significant decrease of its cost, has led to the mainstreaming of this technology, promising to bring high-resolution immersive, simulated experiences to the average consumer. Although the market of VR and its mainstream adoption are constantly growing, still most of the popular immersive experiences are designed to be solitary. The full potential of VR as a medium will not be reached, until immersive virtual worlds widely allow for social presence; meaning “the degree to which a person is perceived as a ‘real person’ in mediated communication” (Gunawardena, 1995). Social presence is linked to the emerging interpersonal emotional connection among the participants of the communication process (Lowenthal, 2010), as well as to the users' satisfaction, when communication is mediated by computers (Gunawardena & Zittle, 1997).

One of the most successful examples of multi-user immersive virtual worlds was AltSpaceVR, which was launched in 2015 and by 2017 was supporting 35000 active users. The users in AltSpaceVR were virtually embodied with the use of avatars, engaged in numerous entertainment activities, browsed the Internet through the platform and developed social relationships with their virtual peers in this virtual world. Despite facing financial drawbacks, the platform was bought in 2017 by Microsoft and was available for most HMD devices, as well as for desktop interfaces. However, in January 2023 it was announced on the AltspaceVR Homepage that the service would shut down on March 10, 2023.

As VR becomes mainstream, more online social VR platforms affording social interaction emerge, such as Spatial.io, JanusVR, vTime, ConVRge, Rec Room, VRChat, High Fidelity and SurrealVR. According to the founder of JanusVR, McCrae (2017), “JanusVR allows a spatial walk through the internet [...] webpages are rooms, and links connect rooms via portals (doorways which seamlessly connect rooms). [...] The experience is collaborative - multiple people can navigate virtual spaces together, communicating via voice or text, sharing portals to discover new areas as a group.” With the development of numerous such platforms the way people use online media is bound to change, rendering the Internet a place of constant multiuser 3D interactions. Also, certain platforms affording social interaction (eg. Decentraland, AltairVR), are changing the way users create and experience immersive worlds, as they can monetize their content, building on blockchain technology.

While there are several studies and approaches emphasising VR as a communication medium (Schroeder 1996; Schroeder 2002; Marini 2012; Biocca and Levy, 1995, Charitos, 2005), the potential of the second generation of social immersive environments for sustaining content production, human interaction and collaboration remains largely untested. Although research shows that users are interested in engaging in social VR applications (Gunkel et al, 2018), there is still limited empirical and theoretical research on the new generation of immersive social VEs as communication media. Given that the new immersive virtual worlds differ from their older counterparts in their functionality and characteristics, and due to their imminent technological, cultural, and social repercussions, the study of Social VR becomes both topical and significant.

2.2 Definitions of Social VR environments

Following the above, virtual worlds are conceptualised as dynamic frameworks of communication channels, tools and affordances, which allow users to connect, interact with each other and experience shared lived experiences in a synthetic environment (Diamantaki et al, 2018). They constitute new forms of content production and consumption, as well as new conceptual tools for understanding social experience and human subjectivity in the context of the highly mediatized societies of late modernity.

In broad terms, an online social virtual world can be described as "a persistent, simulated and immersive environment, facilitated by networked computers, providing multiple users with avatars and communication tools with which to act and interact in-world and in real-time" (Girvan, 2013). Social interaction is initiated among avatars, which virtually embody users, as well as among avatars and virtual agents too. New types of social relationships emerge, including the nonhuman agent as an integral part of the communication process. The terms used in relevant literature since the beginning of the 90s in reference to these social virtual environments were initially: **Collaborative Virtual Environments** (CVEs) and later **Multi-User Virtual Environments** (MUVEs).

In relevant literature, the first term to refer to multi-user virtual worlds was “Cyberspace”. William Gibson in his 1984 novel Neuromancer described Cyberspace as a “A consensual hallucination experienced daily by billions of legitimate operators, in every nation, by children being taught mathematical concepts... A graphic representation of data abstracted from the banks of every computer in the human system. Unthinkable complexity. Lines of light ranged in the nonspace of the mind, clusters and constellations of data. Like city lights, receding.”

The term “**Metaverse**” was coined by author Neal Stephenson in his 1992 novel Snow Crash. In this novel, he described a persistent virtual world that reached, interacted with, and affected nearly every part of human existence. It was a place for labour and leisure, for self-actualization as well as physical exhaustion, for art alongside commerce. (Ball, 2022, 14)

The Metaverse (Mystakidis, 2022) is the post-reality universe, a perpetual and persistent multiuser environment merging physical reality with digital virtuality. It is based on the convergence of technologies that enable multisensory interactions with virtual environments, digital objects and people such as virtual reality (VR) and augmented reality (AR). Hence, the Metaverse is an interconnected web of social, networked immersive environments in persistent multiuser platforms. It enables seamless embodied user communication in real-time and dynamic interactions with digital artefacts. Its first iteration was a web of virtual worlds where avatars were able to teleport among them. The contemporary iteration of the Metaverse features social, immersive VR platforms compatible with massive multiplayer online video games, open game worlds and AR collaborative spaces. The word Metaverse is a closed compound word with two components: Meta (Greek prefix meaning post, after or beyond) and universe. Regarding online distance education as well as artistic implementations, Metaverse has the potential to remedy the fundamental limitations of web-based 2D e-learning and other creative tools.

Ball (2022, p.33) describes the Metaverse, as: a never-ending virtual world where everyone dresses up as comical avatars and competes in immersive VR games to win points, jumps into their favourite franchises, and acts out their most impossible fantasies. This was brought to life in Ernest Cline's Ready Player One, a 2011 novel considered to be a more mainstream, spiritual successor to Stephenson's Snow Crash, and which was adapted to film by Steven Spielberg in 2018. Like Stephenson, Cline never provided a clear definition of the Metaverse (or what he called "The Oasis"), but instead described it through what could be done and who one could be within it. This vision of the Metaverse is similar to how the average person understood the internet in the 1990s—it was "The Information Superhighway" or "World Wide Web," which we'd "surf" with our keyboards and "mouse"—just now in 3D. A quarter century later, it's obvious that this conception of the internet was a poor and misleading way to describe what was to come.

As both independent game engines and live services suites developed over the past two decades, other companies combined these approaches into a new one: integrated virtual world platforms (IVWPs) such as Roblox, Minecraft, and Fortnite Creative. IVWPs are based around their own general-purpose and cross-platform game engines, similar to Unity and Unreal (Fortnite Creative, or FNC, which is owned by Epic Games, is built using Epic's Unreal Engine). However, they are designed so that no actual "coding" is required. Instead, games, experiences, and virtual worlds are built using graphical interfaces, symbols, and objectives. (Ball, 2022, p.120)

The European Commission adopts the term **virtual worlds** (VWs) in relation to these online digital communication environments. According to the “Communication from the Commission to the European Parliament, The Council, the European Economic and Social Committee and Committee of the Regions” (European Commission, 2023)[2]: “Virtual worlds are persistent, immersive environments, based on technologies including 3D and extended reality (XR), which make it possible to blend physical and digital worlds in real-time, for a variety of purposes such as designing, making simulations, collaborating, learning, socialising, carrying out transactions or providing entertainment.”

In the above-mentioned report of the EC, virtual worlds are also related to the following terms:

- Web 3.0 is the third generation of the World Wide Web. Its main features are openness, decentralisation, and users’ full empowerment enabling them to control and realise the economic value of their data, manage their online identities and participate in governing the web. Semantic web capabilities allow linking data across web pages, applications and files. Decentralised technologies and digital twins enable peer-to-peer transactions, transparency, data democracy and innovation along entire value chains.
- Web 4.0 is the expected fourth generation of the World Wide Web. Using advanced artificial and ambient intelligence, the internet of things, trusted blockchain transactions, virtual worlds and XR capabilities, digital and real objects and environments are fully integrated and communicate with each other, enabling truly intuitive, immersive experiences, seamlessly blending the physical and digital worlds. (European Commission, 2023, p. 1-2)

The multi-user online platforms known as virtual worlds represent, and in many ways simulate, three-dimensional spatial experiences, and provide their users with resources to personalise their communicative environments. These online platforms facilitate multimodal communication and real-time interaction in computer-generated representations of three-dimensional space by the use of avatars. The socio-technical characteristics of interaction in these virtual places provide specific affordances for verbal and non-verbal communication (Schroeder, 2011) and the use of avatars as personal mediators (Jensen in Gürsimsek, 2014). Furthermore, the visitors and creators of these spatial representations interact, socialise and cooperate for various purposes thus, socially transforming VWs into meaningful places through their interactive experiences.

2 Communication from the Commission to the European Parliament, The Council, the European Economic and Social Committee and Committee of the Regions, URL: https://digital-strategy.ec.europa.eu/en/library/eu-initiative-virtual-worlds-head-start-next-technological-transition

Virtual worlds are seen as an important part of this transition to Web 4.0. They are already opening up a wide range of opportunities in many societal, industrial and public sectors (European Commission, 2023, p.1). Virtual worlds can boost the cultural and creative industry, from fashion to video games, cultural heritage, music, visual arts and design, by offering new ways to create, promote and distribute European content and engage with audiences. (European Commission, 2023, p.4)

Ultimately, the Commission's vision and strategy aims for a Web 4.0 and virtual worlds that reflect EU values and principles and fundamental rights, where people can be safe, confident and empowered, where people's rights as users, consumers, workers or creators are respected, and where European businesses can develop world-leading applications, scale up and grow. Furthermore, the Commission aims for a Web 4.0 that is powered by open and highly distributed technologies and standards that enable interoperability between platforms and networks and freedom of choice for users, and where sustainability, inclusion and accessibility are at the core of technological developments. The EU's Single Market, rich and diverse culture, creative content, strong industrial base, excellence in research, innovation and education, and robust legislative framework should be drivers to Europe's leadership, competitiveness and technological sovereignty in this field. (European Commission, 2023, p.4)

The identification of Metaverse and characteristics of VWs, according to the above-mentioned definitions, is intended to delimit the boundaries for the analysis of application requirements in the following steps of D.2.1.

3 Investigating case studies of using MUVEs for presenting Cultural Heritage content

The integration of immersive technologies, such as Virtual Reality (VR) and Augmented Reality (AR), represents a significant advancement in the field of cultural heritage presentation and online publication. These technologies address the limitations inherent in traditional methods by offering novel, interactive experiences that transcend temporal and spatial constraints. Recent academic research has elucidated the ways in which VR and AR can enhance the accessibility, inclusivity, and engagement of cultural content.

Cecotti (2022) explores the integration of cultural heritage within fully immersive VR environments, highlighting the transformative potential of VR technology in digitally preserving and presenting tangible, intangible and natural cultural inheritance. By delving into the methodologies and technologies employed, Cecotti (2022) highlights the capacity of VR to foster immersive engagements with cultural heritage, transcending temporal and spatial constraints, allowing for broader access with improved inclusion, diversity, and equity of a wider audience. More specifically, the categorization of several applications is attempted, based on their content, ranging from broad art galleries to focused exhibits on specific artworks or artists.

Moreover, various methods for assessing the performance of such applications are evaluated, including workload, usability, flow, and potential VR symptoms surveys. Challenges related to interdisciplinary collaboration, educational deployment, gamification aspects, and social interaction are discussed, emphasising the necessity for cultural heritage practices within virtual environments to encompass the inclusion, diversity, equity, access, and success (IDEAS) principles. Despite the absence of synchronous social experiences in most of the current VR applications, users can still share experiences and interact asynchronously through digital tools like discussions and reviews. Furthermore, a growing trend involves the inclusion of virtual humans in cultural-related VR applications to enhance immersion and scale perception.

Li and Cesar (2023) provide an extensive overview of Social VR applications and user experiences, delineating various Social VR platforms and their attendant features, including the field of cultural heritage. More specifically, the authors provide an overview concerning the design, implementation, and real-world deployment of social VR applications across various domains, which facilitate distant interpersonal communication within contexts such as personalised healthcare, celebratory events, interactive exploration of cultural heritage, and immersive entertainment experiences.

They further focus on two experimental methodologies pertaining to the creation and validation of a social VR questionnaire through a user-centric approach, as well as the assessment of visual fidelity of photorealistic avatar representations through different degrees of freedom (3DoF and 6DoF). The authors reach the conclusion that the advancement of Social VR necessitates the establishment of standardised protocols encompassing both qualitative and quantitative measures to evaluate user interactions. Furthermore, there is a need for standardised procedures dictating the deployment of Social VR applications within real-world settings such as hospitals and museums.

Giovannini and Bono (2023) present a case study on the creation of virtual reality experiences within a social virtual environment, and more specifically Mozilla Hubs, probing the fusion of physical and digital spaces to engender phygital exhibitions. The case study endeavours to create a digital replica of the temporary Phygital Exhibition held at the Sordevolo Passion Museum in the Church of Santa Marta, commencing in July 2022. Unlike the museum's permanent collection, which narrates the tradition of popular theatre in Sordevolo concerning the Passion of Christ performance, the Phygital Exhibition centres on documenting the design and construction of the scenography. Within the virtual environment, the physical space is replicated with minimal detail to emphasise the VR exhibition, featuring interactive panels showcasing historical documentation, drawings, and images. Additionally, the virtual space incorporates video content and 3D models unavailable in the physical space, providing insights into the evolution of the scenography over time.

By integrating physical artefacts with digital content, Giovannini and Bono (2023) exemplify the potential of social VR to transform the way we engage with cultural heritage, blurring the boundaries between the physical and virtual worlds. The authors explore the digital curation of immersive and virtual environments within the cultural heritage sector, with their primary research objective focusing on the establishing a methodological and operational workflow for developing virtual environments using social virtual environments.

Ch’ng et al. (2023) investigate the case of social augmented reality, giving insights into its capacity to facilitate communication and interaction around cultural heritage. By overlaying digital content onto physical environments, the developed augmented reality application blurs the boundaries between the physical and virtual realms, offering users unprecedented opportunities to engage with cultural artefacts and sites in situ. More specifically, within the context of this study, a mobile augmented reality application has been developed aiming to multi-user interaction, exploring the replication and expansion of discussions around cultural heritage objects, in order to shed light into social communication dynamics within augmented reality applications when co-viewing heritage objects.

3.1 A general overview of case studies of developed VEs as contexts for the presentation of CH content

As presented in the previous section, VR has significantly transformed the field of cultural heritage by providing innovative ways to not only document and present CH artefacts, sites and practices but also to re-interpret them, make them more accessible to a wider audience, and engage audiences in novel ways. In this section we present an overview of selected case studies of multi-user online VR environments for Cultural Heritage. The majority of these experiences allow multiple visitors from remote locations to interact and navigate inside the virtual environments, simultaneously. Some of the selected case studies support access and interaction between more than one user via local networks, rather than the internet. Finally, there are a few case studies of online single-user cultural heritage VR applications.

These VR applications follow various approaches regarding the integration and use of CH content. Some of them recreate CH artefacts, monuments, and sites, ensuring that they are preserved digitally, and they can be accessed easily by a broader audience. In cases of CH items that have been destroyed or significantly altered over time, their virtual reconstructions provide a way to visualise and understand how these items looked and functioned in their original context. Additionally, in some cases, visitors can interact with the virtual CH items in ways that are often impossible with the material CH items. An additional advantage of online VR environments is that they remove geographical barriers, allowing people from all over the world to access cultural heritage sites and artefacts remotely. Visitors can also virtually experience intangible CH practices by immersing themselves in interactive environments that revive these practices. VR storytelling enhances visitors' experiences by allowing them to engage with CH content in emotionally engaging and memorable ways. Lastly, some of the presented case studies allow users to engage in collaborative activities with the objective of exploring or reappropriating CH items. The selected case studies span from informal educational environments and edutainment projects to virtual museums or exhibitions.

One of the primary instances is VIVE ARTS[3], which offers users a platform to explore virtual art galleries and exhibitions, transcending the constraints of physical space and fostering enriched engagement with art and culture, through the implementation of VR, XR and blockchain technologies. By adopting the aforementioned technologies and artistic content, VIVE ARTS redefines the boundaries of cultural engagement in the digital age, enabling institutions and organisations to experiment in preserving cultural heritage to democratise creation through digital innovation in the arts, reaching a worldwide audience. VIVE Arts is more broadly associated with curating and showcasing

[3] Vive Arts | https://www.vivearts.com/

cultural content in virtual reality, often through individual experiences rather than multi-user social environments.

The Museum of Other Realities[4] stands as a pioneering example of an immersive virtual museum, showcasing digital artworks and interactive exhibits that redefine traditional notions of museum curation and exhibition. By harnessing the power of VR, The Museum of Other Realities creates a dynamic and interactive space for cultural exploration and exchange. The Museum of Other Realities (MOR) represents a paradigm of a multi-user social virtual reality (VR) platform. Functioning as a shared virtual space, MOR enables global users to meet and partake in various activities, including exploration of digital art exhibitions, interactive engagement with fellow visitors, and immersion in curated artworks collectively. By fostering a collaborative environment conducive to interactivity and cultural exchange, MOR epitomises the integration of social dynamics within the realm of virtual reality, particularly in the context of cultural experiences and artistic appreciation.

The 'Silk Road' VR and AR Experience aims to recreate the historical Silk Road through VR and AR technologies, offering users a virtual journey through this historical trade route and its cultural significance. Through a blend of historical narrative and immersive technology, the 'Silk Road' VR and AR Experience provide users with an experiential understanding of the cultural heritage embedded within this ancient trade network. The researchers created a virtual environment developed with Unity 3D game engine. The environment consisted of digitised Chinese relics, containing six photogrammetry reconstructed cultural heritage objects. The CH objects could be experienced through both an HTC Vive Head-Mounted Display and a mobile augmented reality application, serving as an interface connecting the VR and AR worlds. The experience enabled interaction between VR and AR users (Li et al, 2018). For example, when an AR user rotated an augmented object, the same object rotated in the VR environment triggering a sound effect, thus providing visual and auditory cues to draw VR users' attention towards the object (Li et al, 2018). Using the 'Silk Road' Experience as a case study Li et. al. (2018) investigate hybrid VR and AR in a multi-user application and study users' acceptance of the technologies in terms of social influence, performance expectancy, effort expectancy, and behavioural intention (Li et al, 2018).

[4] Museum of Other Realities - https://www.museumor.com/

Figure 1. The 'Silk Road' VR and AR Experience (Li, Y., Ch'ng, E., Cai, S., & See, S., 2018)

Çatalhöyük VR offers users an immersive experience of the ancient Çatalhöyük settlement, adopting VR technology to transport users to this archaeological site and foster engagement with ancient history and culture. By reconstructing the physical environment of Çatalhöyük in virtual space, Çatalhöyük VR enables users to explore and interact with the past in novel ways (Katifori et al, 2021). The immersive experience at Çatalhöyük involves participants engaging in collaborative enactments of simplified cultural activities based on archaeological hypotheses, such as wall plastering and grave offerings. Participants are prompted to reflect on ancient and modern practices and consider their contemporary significance through open-ended questions.

To enhance participant collaboration, a unique interaction mechanism called the 'high five' paradigm was developed, encouraging collaboration while granting users and VR designers greater control over the experience. In order to perform the high five, the user avatars must approach one another and simulate the high five gesture by touching their virtual palms. The high-fiving seemed to support the objective of providing a sense of shared experience of re-enactment, dialogue and reflection. It fostered participants' feeling of "acknowledgement and success for a task, thus contributing towards a positive emotional feedback loop of establishing joint attention to the space, committing together to a task, bringing it to a successful closure and then confirming this success through the gesture" (Katifori et al, 2021). The Çatalhöyük VR experience is implemented through a server based multi-user application and has been developed with the Unity 3D game engine.

Figure 2. Çatalhöyük VR[5]

Santiago de Compostela VR provides users with a virtual tour of the historic city of Santiago de Compostela, enabling exploration of its rich cultural heritage and architectural history (Flores et al, 2000). With the adoption of VR technology, Santiago de Compostela VR creates an immersive and educational experience that transports users to the heart of this historic pilgrimage site. The experience allows for single-user and multi-user interaction, while the project was implemented with the adoption of VRML & Java technologies.

[5] Çatalhöyük VR | source: narralive.itch.io/catalhoyuk-vr

Figure 3. Santiago de Compostela VR (Flores, J., Arias, J. E., Saavedra, S., Varela, E., Ferro, J. M., & Taboada, J. A., 2000)

BEYOND MATTER | Cultural Heritage on the Verge of Virtual Reality is a project aimed at preserving cultural heritage through immersive VR experiences, highlighting the potential of VR to democratise access to cultural heritage and foster a deeper appreciation for the shared human history. More specifically, this practice-based research project delved into multifaceted research activities focusing on the intricacies of virtual reality. By engaging with contemporary shifts in visual art production and mediation within modern and contemporary art museums, BEYOND MATTER addresses the profound impact of rapid advancements in computer science, information technology, and the increasing utilisation of augmented and virtual reality, alongside artificial intelligence. In contrast to physical exhibition spaces, which rely on spatial properties to contextualise artworks, virtual exhibition models offer immersion through the interaction between materiality and representation, irrespective of geographical constraints. BEYOND MATTER aims to explore the interdependence between physical and virtual spaces and understand its implications on art production, curation, and mediation. By investigating the "virtual condition", the project proposes innovative approaches to preserving cultural heritage and harnessing the potentials of digital world-making. Within the course of the project, different research activities have been conducted, including a workshop which took place in Mozilla Hub's online platform, enabling multi-user immersive VR interaction. The workshop took place in a shared immersive virtual reality space built with Mozilla Hubs.

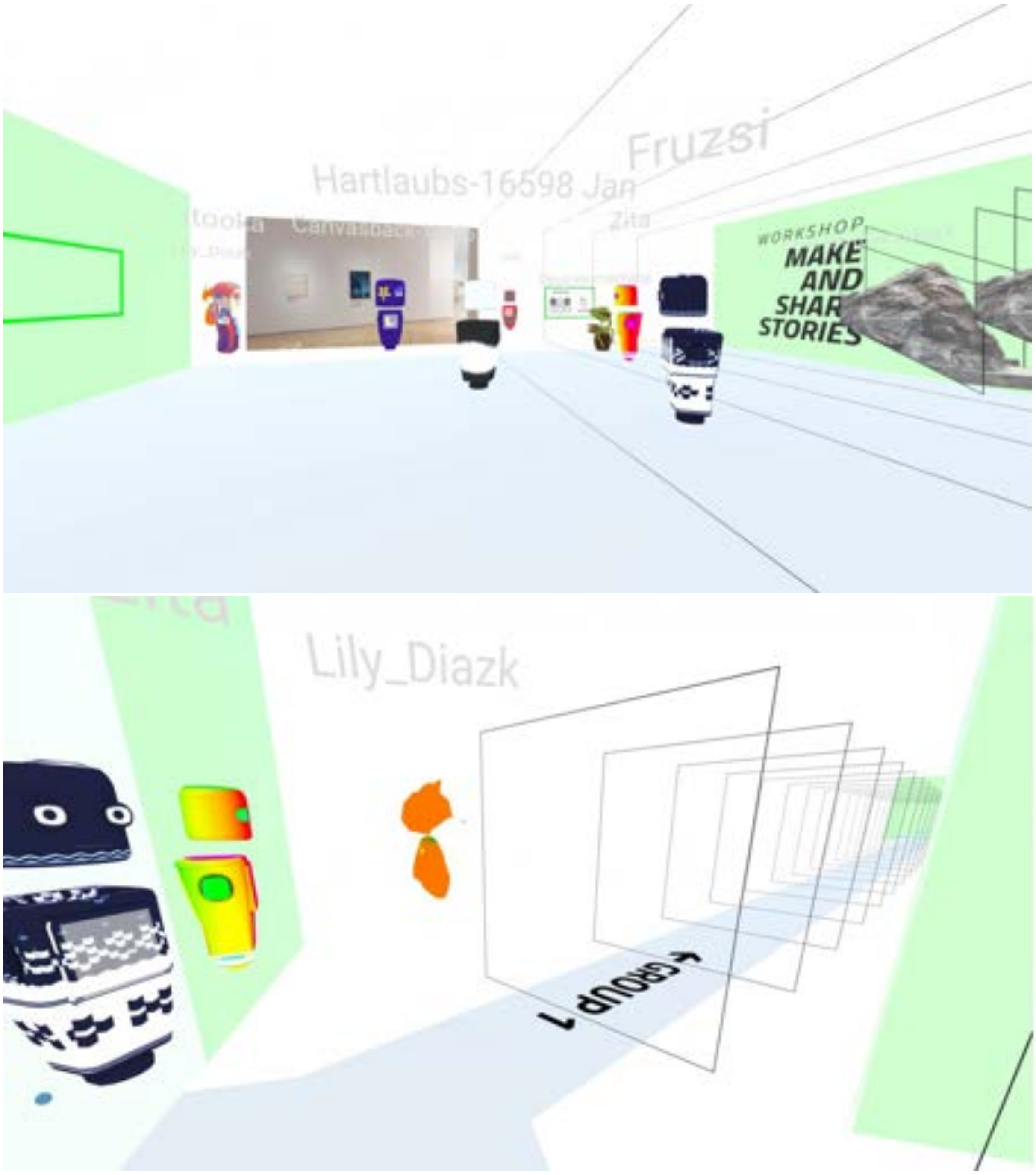

Figure 4. 'Make and Share Stories' PORe Workshop, Beyond Matter project.[6]

[6] Make and Share Stories' PORe Workshop, Beyond Matter project **|** source: https://beyond-heritage.aalto.fi/pore-workshop-model1/

Participants, workshop facilitators, and tour guides gathered online and interacted as avatars. The first session of the workshop introduced participants to the art exhibition "Spatial Affairs" of the Ludwig Museum. Participants had the opportunity to learn more about a number of selected artworks via a polyvocal immersive guided tour. In the second session of the workshop participants were encouraged to actively participate in interactive tasks within the virtual world. These creatively engaging activities, which focused on two artworks from the guided tour, allowed participants to reflect and share their own accounts of the exhibition with the group, create their own narrative in the virtual space and to add their voices to the existing exhibition narratives.

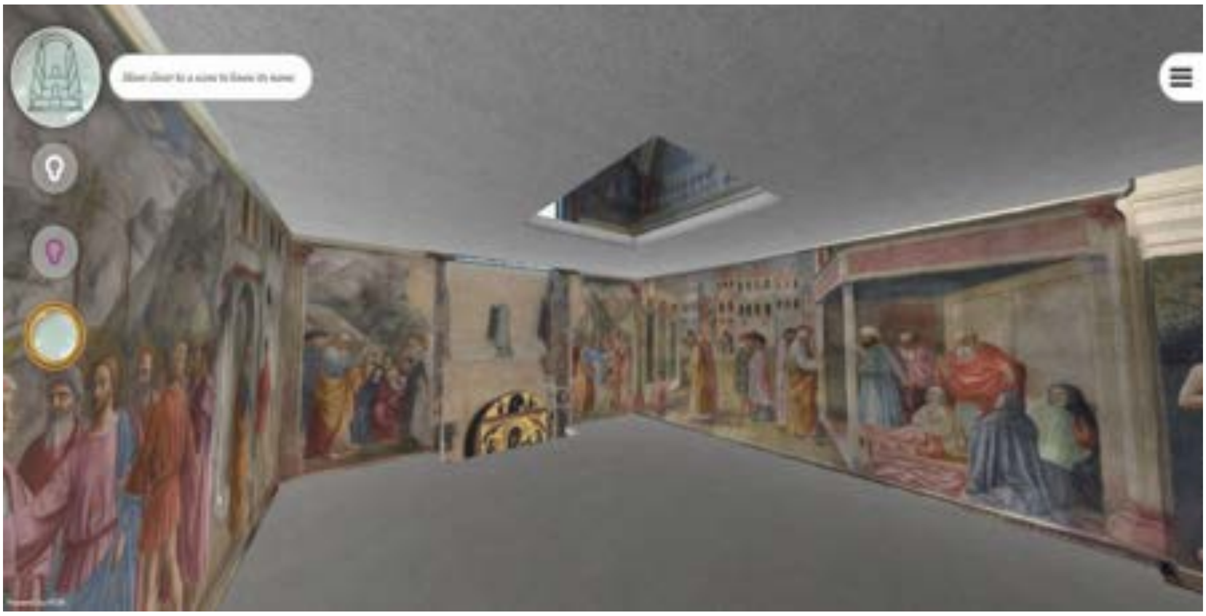

Figure 5. Brancacci POV[7]

The ATON Framework, an open-source platform built upon Node.js and Three.js technologies, stands as a pivotal tool in the creation of immersive Web3D/WebXR applications for interacting with cultural heritage objects and 3D scenes on the Web. Developed by Fanini et al. (2021), ATON offers a versatile solution for the presentation and dissemination of interactive 3D content on desktop and mobile web browsers tailored to cultural heritage contexts. With the adoption of web-based technologies, ATON enables the seamless integration of interactive and collaborative experiences, contributing significantly to the preservation and dissemination of cultural heritage assets. A notable case study showcasing the capabilities of ATON is the Brancacci POV Prototype, which explores the renowned Brancacci Chapel—an architectural monument of the Renaissance located in Florence, Italy. The Brancacci POV Prototype was developed as a multi-user hybrid and collaborative VR experience, as presented by Pescarin et al. (2023), and exemplifies the collaborative and guided nature of ATON-based applications. By integrating immersive technologies, such as virtual reality (VR) and augmented reality

[7] Brancacci POV | (source: app.brancaccipov.cnr.it/a/brancapp/)

(AR), the Brancacci POV Prototype offers users an enriched exploration of cultural heritage sites, fostering user engagement, social cohesion between the users and knowledge dissemination.

ArchiSearch[8] is an online collaboration platform developed by the School of Architecture Engineering at the Technical University of Crete, that utilises virtual reality to facilitate architectural exploration and design, analysis and modelling of buildings and monuments. Through immersive VR experiences, users can navigate architectural spaces, collaborate with peers, and engage in real-time design discussions. Implemented using web-based VR technologies (NVIDIA RTX hardware-software platform, combining Artificial Intelligence and Ray Tracing), ArchiSearch offers multi-user VR experiences, enabling collaborative design sessions across geographical boundaries.

The Da Vinci Effect project explores the intersection of art, science, and technology through immersive experiences inspired by Leonardo da Vinci's works (Rizvic et al, 2022). With the adoption of VR technology, the project presents interactive exhibits and educational content, allowing users to delve into da Vinci's art and scientific inquiries. More specifically, the project is a multiplayer VR game designed for teenagers with the aim of familiarising them with the works of Leonardo da Vinci and his significant contributions to human history. A novel approach employed in the application involves the use of the ''inside-out'' tracking capabilities of Oculus Quest and Quest 2 mobile VR headsets, enhancing the immersive experience for users.

The Museum of the Future initiative[9] aims to unlock shared cultural heritage experiences through social virtual reality. By creating immersive VR environments, the project allows visitors to explore cultural artefacts and historical sites collaboratively. The first application developed within the context of the project is MediaScape XR, which represents a pioneering effort in adopting VR technology to transform visitor experiences within cultural heritage institutions. As the physical museum undergoes renovation, MediaScape XR offers visitors an immersive journey through a virtual representation of the museum environment, allowing them to interact with iconic cultural artefacts, such as Jerney Kaagman's costume from the TopPop show.

Beyond providing access to physical museum spaces, MediaScape XR demonstrates a shift towards utilising digitised collections to create engaging and interactive experiences. By incorporating elements of gamification, education, and experience design, MediaScape XR fosters active exploration and engagement with cultural heritage. With the use of the VRTogether platform and CWI Point Clouds software suite,

[8] ArchiSearch | https://www.archisearch.gr/press/online-collaboration-virtual-reality-metaptyxiako-chania/

[9] Museum of the Future | https://beeldengeluid.nl/en/knowledge/blog/museum-future-social-virtual-reality-unlock-shared-cultural-heritage-experiences

MediaScape XR enables multiple users to connect and collaborate within the same virtual space, transcending physical barriers and fostering social interaction. This integration of VR technology not only enhances visitor experiences but also facilitates the democratisation of access to cultural heritage, heralding a new era of immersive and inclusive museum experiences.

Edify is an advanced platform for immersive learning, developed by Edify Global Holdings, which focuses on providing virtual reality educational experiences tailored to various industries, including higher education and enterprise training. With the adoption of real-time collaboration tools like Zoom and Microsoft Teams, and virtual environments, Edify enables users to engage in interactive learning scenarios. These scenarios range from virtual labs to complex technical training sessions, designed to foster hands-on, experiential learning in a digital format. Edify offers a no-code authoring environment, allowing educators and trainers to design custom virtual experiences without the employment of programming skills. This flexibility enhances the platform's accessibility, making immersive learning tools widely available to institutions and businesses.

A particularly interesting use case for Edify is in the preservation and education in the field of cultural heritage. The platform's ability to recreate historically or/and culturally significant sites in virtual space offers a novel approach to cultural heritage education. More specifically, the Burns Beyond Reality project[10], a collaboration between Edify and the University of Glasgow's Centre for Robert Burns Studies, demonstrates the intersection of technology and literary heritage preservation through immersive virtual reality technology. This project reimagines Robert Burns's famous poem Tam O' Shanter in VR, allowing users to explore "Alloway's auld haunted kirk" and other settings in vivid detail. The experience, which provides access to rare artefacts, addresses the limitations imposed by the COVID-19 pandemic by facilitating virtual Burns Suppers globally, enabling participants to experience the poet's legacy remotely.

The project was initiated by Dr. Pauline Mackay, whose expertise in Robert Burns Studies led her to explore new methods of commemorating Burns's legacy. Her vision involved using VR to capture the dramatic imagery, allowing global audiences to engage with Burns's work in ways that transcend the spatial and temporal restrictions, showcasing the potential of VR for cultural education. Additionally, Burns Beyond Reality served as the conclusion of a two-year project that mapped over 2,500 Burns Suppers held worldwide, highlighting the global significance of these gatherings. The project's innovative use of VR was demonstrated during the unveiling of David Mach's Flying Haggis sculpture, attended virtually by over 800 participants. This event, broadcast through Edify,

[10] Burns Beyond Reality | https://www.edify.ac/use-cases/burns-beyond-reality

exemplified the transformative capacity of digital technologies to bring together diverse audiences and foster a shared appreciation of cultural heritage.

Beyond Burns Beyond Reality, Edify extends its VR solutions to broader cultural and educational sectors, such as theatre production and historical education. By creating immersive environments like virtual replicas of the Gutenberg Press and classic theatre stages, Edify allows educators and students to explore these settings and tools without the restrictions of physical access.

Cultural Universe[11] is a pioneering project launched by Saudi Arabia, introducing a cultural metaverse that blends virtual reality with cultural experiences. With the adoption of VR technologies, the project aims to offer users immersive journeys through Saudi Arabia's rich cultural heritage, including historical landmarks, museums, and traditional arts. While specific implementation details are not provided, Cultural Universe promises to revolutionise cultural engagement through virtual reality experiences.

Some other interesting single user cultural heritage applications include ChronoscopeVR[12] and HERIVERSE[13]. More specifically, Chronoscope VR is a VR application that allows users to visit the Acropolis of Athens at the height of the Golden age during the 5th century BCE. HERIVERSE is an augmented reality application focused on cultural heritage exploration and storytelling. Available on mobile devices, the app enables users to discover cultural landmarks, monuments, and artefacts in augmented reality.

3.2 An analysis of selected case studies of developed VEs as contexts for the presentation of CH content

In an era where the digital transformation of cultural heritage emerges as a critical frontier in both presentation and engagement, it is crucial to explore and expand upon the utilisation of digitised data across multifaceted applications. Grounded in the importance of enhancing the visual representation and interactive storytelling of cultural heritage, we explore the potential of digital technologies not merely as tools for archiving but as active mediums for reinterpreting and enlivening historical narratives.

In this section we examine exemplary selected case studies, including research conducted by *National and Kapodistrian University of Athens* (NKUA), *Film University Babelsberg Konrad Wolf* (FBKW), and *Heritage Malta* (HM). These case studies implement advanced digital methodologies, including artificial intelligence, 3D environment creation,

[11] Cultural Universe | https://cointelegraph.com/news/saudi-arabia-launches-cultural-metaverse
[12] ChronoscopeVR | https://chronoscopevr.com/
[13] HERIVERSE | https://play.google.com/store/apps/details?id=com.Anipen.ARCultureHeritage&hl=en_US

and so called “environmental storytelling”, as well as user engagement through multi-user interaction. The examination of these case studies aims to present some of the nuanced opportunities emerging in the digital era. Leveraging the insights from exemplary case studies, including NKUA and FBKW internal research and artistic projects, we pave the way for a series of research objectives to be addressed in the IMPULSE project. These objectives, based on WP2 guidelines of the IMPULSE project, are designed to significantly advance the field of digital cultural heritage, offering new paradigms for engagement, education, and visual representation.

Initially we present an XR experience implemented in the course of the BRIDGES project[14]. The experience allows visitors to experience cultural heritage sites through immersive storytelling and interactive elements. The experience is based on a platform that supports multi-user interaction of users that coexist in a shared physical space and/or online. Then, we present a project developed by Film University Babelsberg, illustrating how cultural engagement can be enhanced through technology. Following this, the digital restoration efforts for Notre-Dame de Paris are examined, showcasing how digital tools can aid in the preservation of historic sites. All the above, along with some more relevant cases, underscore the significant impact of digital technologies on cultural heritage.

3.2.1 Case study 1: BRIDGES

The BRIDGES [3] (A hyBRID (physical-diGital) multi-user Extended reality platform as a stimulus for industry uptake of interactive technologieS) initiative represents a holistic solution designed to facilitate remote and co-located group interaction within room-scale immersive eXtended Reality (XR) environments, seamlessly blending physical and virtual spaces. This innovative platform exhibits the potential to be used across various sectors, ranging from manufacturing, engineering, and architecture to education, healthcare, arts, entertainment, and cultural heritage. Through extensive research and validation efforts, particularly focused on industrial training and informal learning/edutainment, the BRIDGES project has conducted thorough assessments in real-world environments, such as major international airports in Germany and Greece for firefighters' training, as well as at the Foundation of Hellenic World for informal learning experiences.

The application “A day in Ancient Athens” cultural heritage experience was built aiming at enhancing informal learning in museums. The experience allows visitors to experience historical settings, like Classical Athens, through immersive storytelling and interactive elements. One of the scenarios designed for the BRIDGES XR platform includes experiencing life in antiquity by travelling back in time. The XR experience is multi-user,

[14] BRIDGES | https://www.bridges-horizon.eu/

designed for groups of up to 5 users that coexist in a shared physical space (potentially the platform supports remote users as well). The physical space matches the structure of the virtual space. The XR platform allows a small group of people to participate in a guided storytelling experience inspired from daily life in Classical Athens, following the activities, festivities and social interactions of an Athenian family in their house. In the scenario, visitors may choose their own character and visit the household of a famous middle class pottery maker and merchant in Ancient Athens. The visitors can physically walk around the house and participate in various activities such as gathering round the hearth to assist the preparation of a meal, preparing offerings to the gods, interacting with objects by using their actual hands and gestures. The XR experience provides additional olfactory stimuli to the visitors (El Raheb, et. al.).

Figure 6. "A day in Ancient Athens" XR Experience, at the Foundation of Hellenic World.
© BRIDGES project

Figure 7. "A day in Ancient Athens" XR Experience, at the Foundation of Hellenic World. © BRIDGES project

In the context of the BRIDGES project, an iterative, user-centred methodology was followed to elicit user requirements and to design various scenarios for the XR experiences. This methodology involves a four-phase process, including the following phases: 1) understanding and describing the context, 2) defining user groups through personas, 3) codifying and categorising user requirements, and 4) eliciting and prioritising user requirements. This process aimed to balance the diverse requirements of different user groups and application contexts. Furthermore, it attempted to create an inclusive XR experience considering the diversity of target users: staff and visitors of museums, cultural heritage and other kinds of informal education or recreational institutions. This target group can show a great diversity in terms of age, motivations, interests, physical condition, profession, language, level of interaction and participation, familiarity with technology, abilities, or cultural background.

At the core of the BRIDGES solution lies the utilisation of the pre-existing Immersive Deck platform, initially developed by the Technical University of Vienna and subsequently enhanced by the SME Illusion Walk, a key industrial partner within the BRIDGES consortium. The Immersive Deck consists of a set of technologies and tools, assembled into a complete, low-cost platform. It includes positional tracking for a group of up to 10 people concurrently. Users wear high-end Head Mounted Displays (HMDs) connected to laptops carried in backpacks, which render locally the virtual world in the HMDs. A stereo camera attached to each HMD performs inside-out optical hand and finger tracking allowing the detection of hand movements for haptic interaction. This setup enables natural interaction and free-roam navigation, by walking in large, even multiple rooms.

The key technical and operational features of the XR platform include: 1) a mixed reality setting of any size and configuration (e.g. multiple rooms, corridors, etc.), combining physical and virtual interaction; multi-user concurrent interaction in the physical and virtual space, supporting a sizeable number (e.g. 10) of co- and remotely-located participants; 2) a low cost solution for tracking the physical area and mapping the virtual world onto the built environment, including the architecture, objects, machinery, equipment and any object related to the scenario of each application; 3) intuitive interaction, where hands and fingers are tracked optically and represented in the virtual world, thus eliminating the need for hand controllers; users can shake hands as they do in real life and navigate the virtual naturally by physically walking around in the real world; 4) multi-sensorial stimulus, improving immersion and maximising the feeling of presence by incorporating effects such as wind, heat, smell, vibration, in addition to the visual, auditory and tactile (El Raheb, et. al.; Schönauer, et. al.)

The platform also offers a highly immersive environment, enriching training and learning experiences through immersive XR technologies to foster engagement and retention. Additionally, its modular and customizable system ensures adaptability and flexibility, catering to diverse user requirements and scenarios, thus ensuring seamless integration within different contexts.

Figure 8. "A day in Ancient Athens" XR Experience, at the Foundation of Hellenic World. © BRIDGES project

3.2.2 Case Study 2: "The Lost Time" - A VR Journey through History

"The Lost Time" implemented by Film University Babelsberg KONRAD WOLF offers an immersive 6 Degrees of Freedom (6 DOF) cinematic virtual reality experience that meticulously recreates the environment of the Theresienstadt ghetto and concentration camp using advanced scanning and photogrammetry. Alongside this, the project brings to life a 1930s Berlin apartment and Auschwitz concentration camp to set the stage for a deeply moving narrative.

This VR journey is anchored in the life of Margot Friedländer, a Holocaust survivor, who shares her harrowing experiences from one of history's darkest periods. The story begins in Berlin, 1943, as Margot's mother and younger brother Ralph are arrested by the Gestapo and deported. Unaware of her family's fate, Margot finds refuge in the Berlin underground. However, after 15 months in hiding, she is captured and sent to Theresienstadt, holding onto the hope of reuniting with her family. Upon her arrival, Margot is faced with the devastating reality that both her mother and brother had been murdered in Auschwitz.

Figure 9. "The Lost Time" by Film University Babelsberg Konrad Wolf

Figure 10. "The Lost Time" by Film University Babelsberg Konrad Wolf

Figure 11. "The Lost Time" by Film University Babelsberg Konrad Wolf

"The Lost Time" leverages the power of digital technology to preserve and convey historical narratives, providing an educational tool that immerses viewers in the personal and collective tragedies of the Holocaust. Through the recreation of significant historical sites and personal stories in VR, the project offers a unique and impactful way to foster empathy and understanding, inviting a deep, interactive engagement with history.

3.2.3 Case Study 3: Digital Renaissance in the Wake of Tragedy - The Restoration of Notre-Dame de Paris

The devastating fire at Notre-Dame de Paris vividly illustrated the urgent necessity for proactive preservation and underscored the vital role digital technologies play in the conservation and restoration of cultural heritage. This tragic event not only emphasised the fragility of our historic monuments but also showcased the innovative ways digital resources can aid in their recovery and preservation.

A notable aspect of Notre-Dame's restoration effort involved the utilisation of a detailed 3D model from the video game "Assassin's Creed Unity," developed by Ubisoft. Caroline Miousse, a senior level artist at Ubisoft, had dedicated years to the cathedral's digital recreation, achieving an extraordinarily detailed representation that meticulously mirrored the actual architecture, down to the texture and form of individual bricks.

In parallel, the comprehensive 3D laser mapping conducted by the late art historian Andrew Tallon provided an invaluable resource. Tallon's work, capturing the cathedral with precision accuracy to within five millimetres through over one billion data points from more than 50 locations, offered a highly detailed and precise digital blueprint of Notre-Dame prior to the fire.

The synergy between Miousse's digital reconstruction and Tallon's laser scans exemplifies the transformative potential of digital tools in cultural heritage preservation. These digital assets have become crucial to the ongoing and meticulous restoration efforts, providing accurate measurements and a deep understanding of the cathedral's structural nuances. This case study highlights the indispensable role of digital innovation in the restoration processes, demonstrating how such technologies are critical in ensuring the resilience and continuity of our cultural heritage in the face of unforeseen calamities.

Through the lens of the Notre-Dame restoration, we see a broader mission crystallise: to employ digital innovation not merely as a preservation tool but as an essential instrument in the restoration, revitalization, and enduring safeguarding of the world's cultural heritage.

Figure 12. Notre-Dame's digital restoration

Figure 13. Notre-Dame's digital restoration

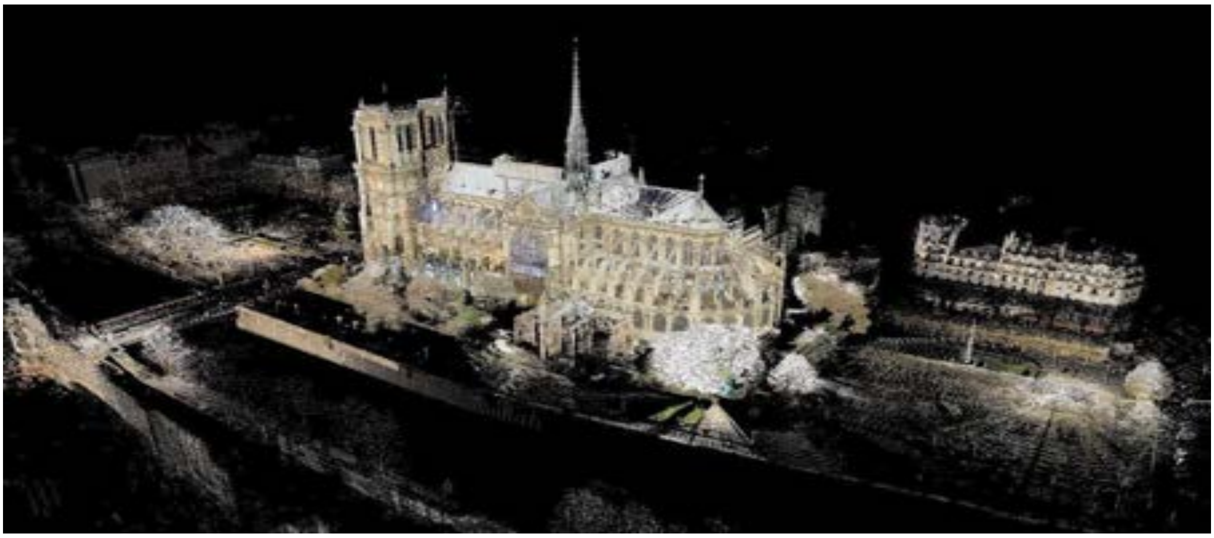

Figure 14. Notre-Dame's digital restoration

The integration of VR and AR technologies and applications in the Cultural Heritage field has transformed the way users engage with the historical content. Implementations of Mixed Reality advanced technologies have created immersive environments for users to interact with, offering a more realistic experience. The following projects highlight the potential these technologies have in enhancing the users' experience in cultural heritage virtual representations.

3.2.4 Case Study 4: Underwater Malta Virtual Museum

The Underwater Malta - Virtual Museum[15] is a project by the Underwater Cultural Heritage Unit of Heritage Malta. The initiative aims to make Underwater Cultural Heritage (UCH) sites accessible to the public and promote the preservation of maritime history through immersive technologies, including Virtual Reality. Underwater Malta also engages in historical research to provide context to each site, making the museum both educational and visually engaging (Gambin et al, 2001a).

The sea is often described as the world's largest museum, containing traces of human existence that have a cultural, historical or archaeological character, including an estimated three million shipwrecks, their cargoes, aircraft wrecks, submerged prehistoric cultural landscapes, submerged ports, and harbour structures (Gambin et.al, 2001). UCH offers invaluable insights into human history yet remains largely inaccessible to the broad public. While diving provides physical access to some sites, the vast majority of UCH remains out of reach. The UNESCO Convention has emphasised in-situ preservation and public sharing of these underwater sites, by balancing scientific research, protection, and the promotion of responsible access to underwater cultural heritage sites (Gambin et al, 2001b).

Underwater Malta aims at addressing this challenge by using 3D photogrammetry, Virtual Reality and other digital technologies to document and display UCH sites. The Underwater Malta website is dedicated to showcasing Malta's underwater cultural heritage. It features a virtual museum where visitors can explore 3D models of underwater archaeological sites, such as shipwrecks and aircraft from various historical periods, including World War II. The Virtual Museum allows the visitors while they are exploring the sites online to decide to click on the different 3D models and zoom in and out and look at them from different angles. The digital visitors have the option to view the models via immersive VR as well. There are annotations with details and information about each underwater model. Only the models have been scanned and

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not the whole archaeological sites, therefore allowing a fragmented but detailed experience.

Figure 15. 3D model of the SS Polynesien shipwreck © Underwater Malta - Virtual Museum

The creation of virtual 3D models involves multiple steps, including remote sensing surveys, diver documentation, and data processing. Remote-operated vehicles (ROVs) and underwater robotics are used to capture data, especially for deep-water sites. High-resolution cameras, drones, and 3D modelling, and photogrammetry software are employed to reconstruct and display these cultural sites online (Gambin et al, 2001a). The data gathered throughout the data capture process was used to produce various visualisations:

- A still from the 3D reconstruction of the wreck onto a matching seabed, that is presented on the landing page of Underwater Malta.
- A 3D model that is simple to navigate and is fast to load. This is used for the landing page of the wreck-specific sub-site. These models are supplemented by annotations and links to other assets for that same wreck. Textual information on the background and history of the site, as well as archival photos and videos, are also included.
- A video "flythrough" of the wreck, taking the viewer through a fixed path that simulates a diving experience, and allows for a diver's perspective.
- A full 3D model that can be zoomed, spun around, and examined at a detailed level. This allows the visitor to use a VR set to experience the model in a 1:1 scale. (Gambin et al, 2001a)

Various visualisations ensure that users with varying background in computer literacy could experience and interact with the online platform and access information about the displayed UCH sites.

The 3D models have been created through photogrammetry. The data for the 3D models was captured using both video and stills. The sites presented on Underwater Malta lie in waters of various depths, ranging from 2 m to 120 m. The University of Malta used a low-cost 3D modelling process, using Structure from Motion (SfM) photogrammetry. In order to reconstruct models of UCH sites lying in deep waters the deep-water photogrammetry process was developed (Gambin et al, 2001a).

Figure 16. 3D model of the Maryland wreck © Underwater Malta - Virtual Museum

Underwater Malta bridges the gap between in-situ preservation and public engagement by offering virtual access to Malta's rich underwater cultural heritage. The way that VR has been approached so far focuses on accessibility, engagement and educational impact. More concretely, VR makes it possible for a global audience to experience Malta's rich underwater and historical sites, which would otherwise be inaccessible due to physical, logistical, or preservation constraints. VR serves as a medium for digital preservation, capturing detailed 3D models of fragile sites, which can be studied and enjoyed without risking damage to the originals. By offering immersive and interactive experiences, VR captures the interest of diverse audiences, including younger generations, who might not engage with traditional museum exhibits. Finally, the use of VR enhances learning by allowing users to explore and interact with historical

Co-funded by the European Union

environments in a way that is both informative and memorable. This approach encourages deeper understanding and retention of historical knowledge.

3.2.5. Case Study 5: WWII Game: Defending the Island Fort (Work in progress)

This case study is a work in progress by Heritage Malta, consisting of a first-person Virtual Reality game, set in St. Elmo's fort, in Valletta-Malta during World War II. The working title of the project is 'Defending the Island Fort' or 'Defending Fortress Island'. The agency' s goal is to create hybrid experiences where digital information is overlaid on the physical world. This approach potentially enhances the educational or artistic experience by adding interactive layers to real-world objects. During the game, players operate a physical replica of a World War II autocannon, in order to defend St. Elmo's fort from aerial attacks. The focus is placed on creating an experience that balances historical accuracy, with engaging gameplay, using cut scenes and scripted events to guide the player, while creating an educational VR game that aims to engage players in a speculative yet informative portrayal of a significant wartime event.

The use of Virtual Reality is crucial in allowing visitors to experience the sights, sounds, and intensity of a WWII battlefield. By getting immersed into a fully realised 3D environment, players gain a first-person perspective of the historical setting, enhancing the authenticity and educational value of the game. VR technology is leveraged to create a sense of presence, making the player feel as though they are physically situated within the fort.

The game's mechanics are carefully designed to balance realism with accessibility. Players can control a World War II autocannon, the Bofors 40mm gun, targeting enemy aircraft. The gameplay is immersive, with the player's viewpoint restricted to what can be targeted by the cannon, emphasising the intensity and focus required in real-life combat situations.

The game's design is based on the actual layout of St. Elmo's Fort, with attention to detail in recreating the fort's architecture, environment, and wartime conditions. The VR experience is enhanced by historical accuracy, from the types of aircraft attacking the fort to the strategic importance of the location. More concretely, the Bofors 40mm autocannon models provide an accurate and realistic representation of this historically significant weapon. Similarly, the aircraft models within the game reflect a high level of historical accuracy, ensuring a high degree of authenticity in the game.

Through VR, the game delivers a rich sensory experience. Visual elements such as the changing skies, explosions, and the fort's surroundings are rendered in high detail, while the audio design includes authentic sounds of gunfire, aircraft, and ambient battlefield noises. The combination of visual and auditory cues in VR enhances the player's emotional and cognitive engagement, making the game not just an interactive experience but a vivid historical reenactment. Time passing is signified by the changes in the sky. In the game UI designers avoided pop ups with indicators that could interrupt users' immersion. In contrast, they used handwritten scoring boards for the final score and a wristwatch to indicate time and communicate certain key elements to the player.

Figure 17. Prototype of the custom-made replica of the canon, used as an interface for the VR game.

The replica of the auto-canon, functioning as an interface for the VR game, is going to be installed inside the fort of St. Elmo, on St. Anne battalion, at its actual location during WWII. It will be part of the permanent exhibition, and the players will have the opportunity to interact with it and play the game, while being surrounded by a tangible site-specific installation. Therefore, while the game's role would be to capture their attention the historical gravity will mostly be on the surrounding informational video and artefacts prepared and presented by the curators of the museum. This approach ensures that all in-game scenarios and details are more closely aligned with the historical context of the WWII setting, even though player engagement and immersion were considered more important in the game than historical accuracy.

The game is more than just entertainment; it serves as an interactive documentary, allowing players to learn about historical events through playful engagement. By placing players in the shoes of a WWII soldier, the game explores how VR can be used as a tool for education, offering an alternative way to experience and understand history within museum spaces. The game is targeting a combination of more specialised players and casual players, with varying levels of gaming experience and expectations, such as museum visitors, students and people interested in WWII.

Through this case study, Heritage Malta explores how visitors can engage and learn while playing, how games can be used as interactive documentaries and how interactive installations can be incorporated into different historic locations.

3.3 Cultural Heritage in Multi-User VR Applications

3.3.1 Case Study 6: CREATE project

Christou, Angus, Loscos, Dettori & Roussou (2006) present in detail the development and evaluation of a large-scale multimodal virtual reality (VR) simulation designed for visualising cultural heritage sites and architectural planning. The system was created as part of the EU-funded CREATE project and it was demonstrated with a reconstruction of an ancient Greek temple in Messene, the temple of Asclepios.

The VR setup uses a CAVE-like environment featuring head-tracked localization, a dual-arm haptic interface, and 3D sound, all integrated with a realistic physics engine. Users can experience the effort required in constructing architectural elements by conducting tasks such as block stacking. Usability and performance were tested through user studies, comparing haptics-enabled versus haptics-disabled systems, with qualitative evaluations conducted in a museum setting. The VR system is based on detailed 3D reconstructions of the temple, which is achieved through photogrammetry and laser scanning. The VR simulation ran on a SGI computer with the ReaCTor™, a CAVE-like immersive display. Key technologies like CAVELib™, OpenGL Performer™, and the XP scripting language were employed for system integration, providing platform independence and synchronised control of stereo displays, tracking, and haptic interfaces. For this specific simulation complementary to the traditional interaction tools, such as gloves and wands, a custom haptic interface was developed. This haptic interface that allowed natural, two-handed interaction that enabled user's move, recognize texture and control objects with high precision. The haptic interface consisted of two equal robotic devices with serial kinematics each having six degrees of freedom enabling accurate force feedback and object recognition. For force feedback during interaction to be achieved, the haptic and graphic systems were synchronised by ensuring both shared the same geometric environment. Objects defined within the graphics system were made interactive by extending the XP classes, allowing the haptic properties to be assigned within the XP script files, ensuring seamless interaction between visual and tactile elements.

Incorporating 3D spatialized sound was essential for a realistic immersive experience. A large number of sound sources were mapped to a limited number of hardware channels, a task that was achieved through perceptual masking and sound source clustering.

This multimodal VR system offers a powerful tool for exploring cultural heritage, providing an immersive and educational experience that enhances understanding and appreciation of historical sites through advanced interaction modalities.

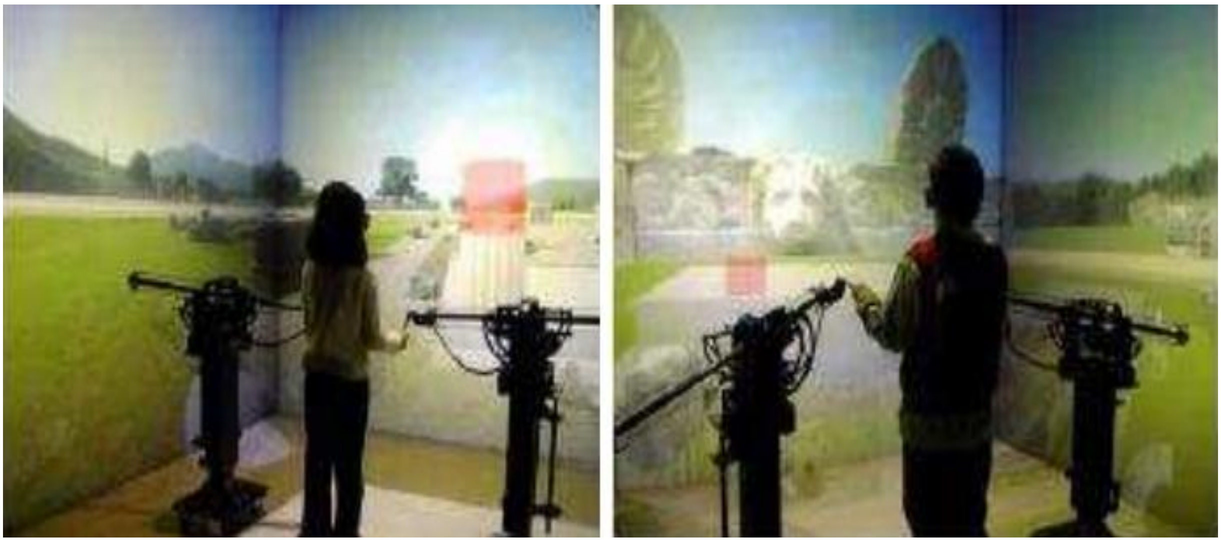

Figure 18. The haptic device inside the cave-like display of the Foundation of the Hellenic World, used by young museum visitors to manipulate elements of the Messene temple (source: Christou et al., 2006, pg. 7)

3.3.2 Case Study 7: Alt-Segeberger Bürgerhaus Virtual Museum

Kersten, Tschirschwitz and Deggim (2017) from the laboratory for Photogrammetry & Laser Scanning of the HafenCity University Hamburg developed a virtual museum for the "Alt-Segeberger Bürgerhaus," allowing remote exploration through two options: an interactive computer-based tour or an immersive 3D experience using the HTC Vive VR system.

The 3D model of the interior and the exterior of the building was created by using IMAGER 5006h terrestrial laser scanner and two digital SLR cameras, Nikon D40 and D90. To capture all the details of the building digital photogrammetry and terrestrial laser scanning were used. This way the visitors could virtually explore the exhibits and understand the history of the building itself. For the development of the application the Unreal Game engine was used as it allowed developers to utilise Blueprints, a visual programming language[16].

The use of the HTC Vive headset in this application offers a highly immersive experience, featuring interactive components, teleportation, and animated visualisations of the building's architectural evolution. The HTC Vive (developed by Valve Corporation in 2016) is a virtual reality headset designed for room-scale VR experiences. The system includes a headset for immersive visuals, two controllers for user interaction, and two “Lighthouse” base stations that track the user's movements by using structured light lasers. The gyroscope, laser position sensors and the accelerometer provide high movement precision. The VIVE controllers are specifically crafted for VR, offering intuitive controls and realistic haptic feedback.

A virtual environment was created after adding the museum’s 3D model in Unreal Engine and utilising the HTC Vive system. This environment offered the users a first-person perspective and allowed them to freely move and explore the museum and its historical context. Visitors were able to navigate large spaces via teleportation and interact with components of the virtual environment using motion-controlled “laser beams” for menu navigation and object selection. Finally, the animated sequences that depicted the architectural history of the building enhanced the immersion and highlighted the VR experience.

[16] Visual programming with Blueprints enables even non-computer scientists to program functions for Virtual museums using graphic elements as it does not require the writing of machine-compliant source code.

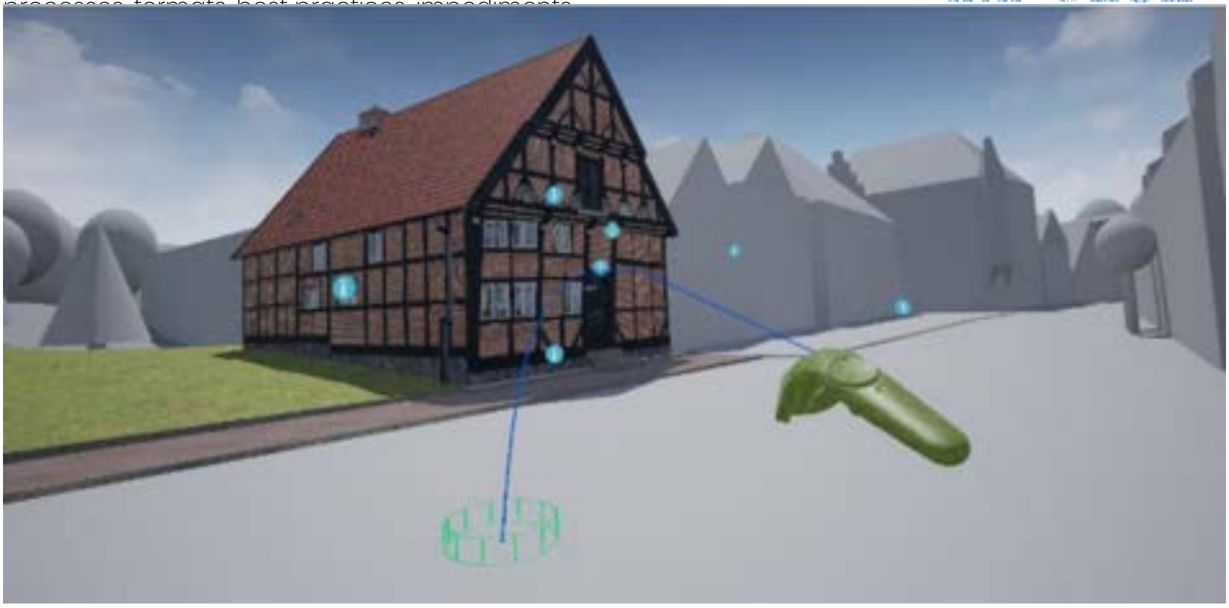

Figure 19. Navigation in the virtual museum Old-Segeberg town house using the developed teleportation function for the virtual reality system HTC Vive (source: Kersten et al., 2017, p. 6)

3.3.3 Case Study 8: The Scottish Lewis Queen Chess Piece

Dima, Hurcombe and Wright (2014) presented the use of AR haptic devices as a means to allow users to “touch” museum artefacts without physical contact.

The artefact used for this research was a 12th-century Scottish Lewis Queen chess piece, displayed in the National Museum of Scotland. The study presented two prototypes, a digital one and a non-digital one, both leveraging the Pepper’s Ghost illusion—a theatrical technique using a glass sheet to project ghostly images. The museum’s display cases themselves were used as a reflecting surface to create the illusion.

One prototype used a 3D-printed replica, mirrored and painted black to minimise reflections. Then the replica was placed at an equal distance from the display glass and facing the original chess piece, so that the user could see their hands reflected on the case when touching the replica, allowing them to experience the sensation of touching the original artefact. The illusion was enhanced by covering the replicated chess piece so that the gaze of the user would focus only on the original artefact.

The second prototype employed a Sensable™ Omni 6DoF (Degree of Freedoms) haptic device, enabling users to feel a haptic model of the chess piece through a pen-like stylus, providing both visual and tactile feedback. The artefact was laser-scanned and a haptic model was created from that scan. The haptic model was placed at an equal distance from the display case as the original chess piece and the haptic device was placed so that the reflection of the pen-like stylus would be positioned close to the artefact in the displaying case. Though the haptic version was invisible, the model could be traced and physically felt using the stylus.

The utilisation of VR and AR technologies in the cultural heritage field has proven to be transformative, as it introduces users to interactive and immersive experiences that surpass the traditional methods. The projects mentioned above present the diversity of applications that can be developed using these technologies. VR and AR can revolutionise the way users approach, perceive and explore cultural heritage by enhancing their experience. The continuous advancement of these technologies could inevitably shape the future of cultural heritage visualisation.

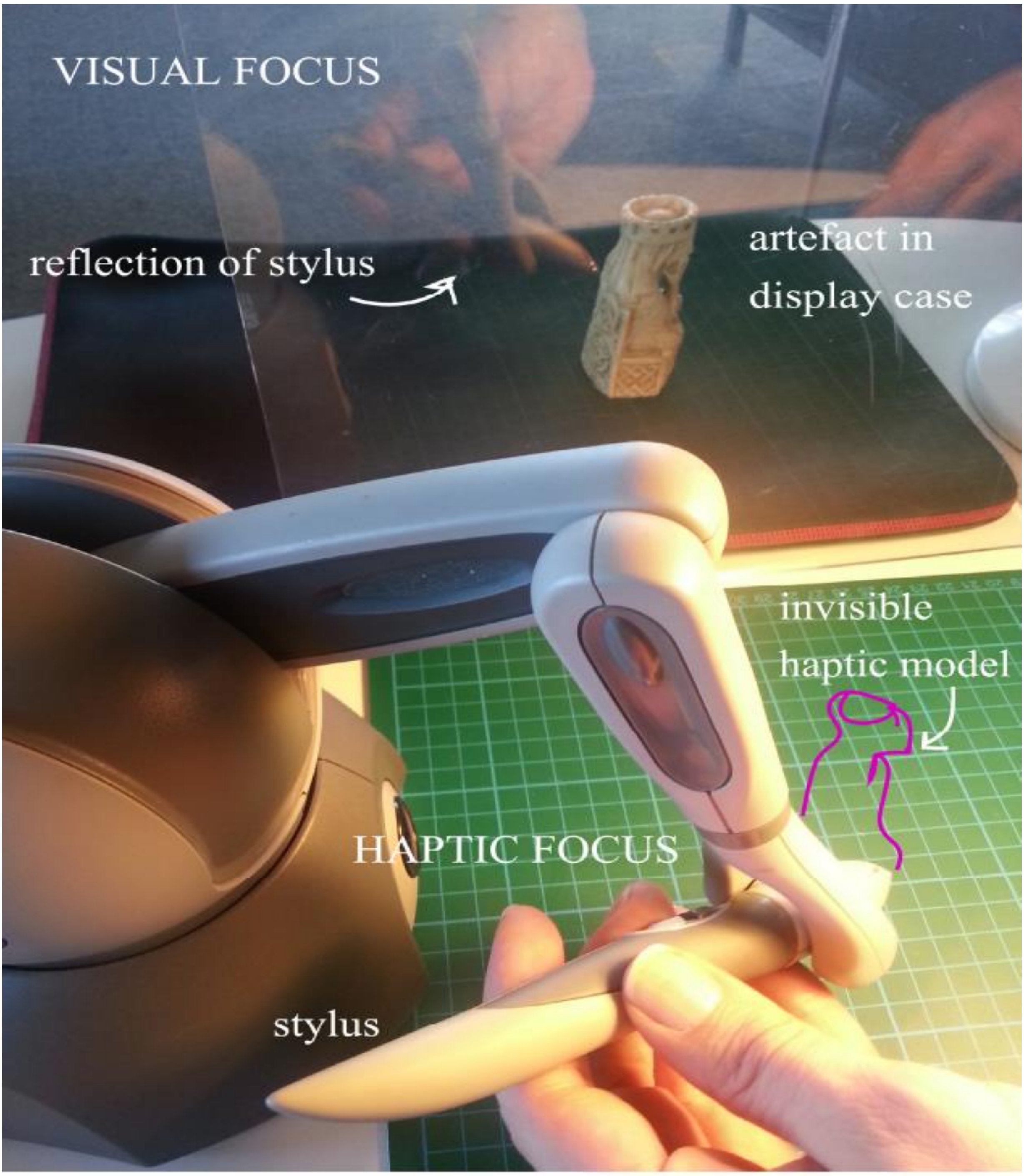

Figure 20. The Haptic Device Prototype (Source: Dima et al., 2014, p. 6)

3.3.4. Case Study 9: The FIRB Project and The Virtual Museum of Ancient Via Flaminia

Forte, Pietroni and Dell'Unto developed research projects that focused on virtual archaeology and on the communication and study of cultural heritage through multi-user virtual reality applications. For this research two case studies were presented: The Virtual Museum of Ancient Via Flaminia and the FIRB (Funds for the Investments of Basic Research) project, "Integrated Technologies of Robotics and Virtual Environment in Archaeology" (funded by the Italian Ministry of Research). The first one has been available in the National Roman Museum of Rome since 2008, while the second one is still in progress but can be accessed through the web since 2008. The FIRB project allowed the creation of a multi-user web domain aimed at a multidisciplinary scientific community. Collaborating with the Department of Archaeology of the University of Pisa and Scuola S. Anna, the project focused on three archaeological sites: Teban tomb 14 in Gurna-Luxor, Temple A in Fayum Medinet Madi, and the ancient settlement of Khor Rori in Oman. These sites varied in characteristics and thus required different technologies for data acquisition, processing, and representation. The virtual environment that came as a result, enabled real-time interaction, hypothesis testing, and collaborative data sharing, supporting continuous evolution and re-elaboration of 3D models and simulations. Users could interact with the 3D models, make modifications, and create new contexts, enhancing learning and scientific communication within the virtual space.

Figure 21. TT14, Gurna- Luxor: 3D model of TT14, obtained from scanner laser acquisition (Source: Forte et al., 2008, p.6)

Co-funded by the European Union

According to Forte, Pietroni and Dell'Unto, the Virtual Heritage Lab of CNR ITABC developed a research and communication project· a Multi-user Virtual Reality installation focusing on the archaeological landscape of ancient Via Flaminia, supported by Arcus S.P.A. The initial part of the road of ancient Via Flaminia was reconstructed by the Virtual Museum of Ancient Via Flaminia, digitising 4.45 acres of terrain. The Milvius Bridge, the area of Grottarossa, Livia's Villa, and the ancient Roman arch of Malborghetto, built by the emperor Constantine were the archaeological sites that were included in the communication system as monographic levels of exploration. According to the different levels of resolution, accuracy, perceptive impact and datasets available for each site, every site was documented through integrated technologies such as topographical survey with GPS, scanner laser, photogrammetry, GISs, total laser station, computer vision, digital photos from aerostatic balloon etc. The avatar-mediated VR system is planned for 4 interactive platforms and an HD stereo display for all the public present in the room.

The users will interact in the same virtual space, each one using their own avatar from one platform. Inside the virtual environment, aiming to the discovery of cultural, interpretative and narrative contents associated with the 3D space users share purposes and perform joined actions. A large screen is installed and, wearing 3D glasses, the visitors can watch the real-time movements and actions of the avatars inside the virtual scenario from different points of view. Every time a user discovers a narrative content, interaction on every platform stops and users together with the public can attend a projection of a movie on the large screen. This way a collective experience of common learning is achieved. The immersive experience combines VR exploration, multi-user interaction, storytelling, and stereoscopic vision to engage both tech-savvy and general audiences. Historical characters within the VR environment narrate stories and describe daily activities, bringing the space to life and deepening visitors' understanding of cultural and historical contexts.

3.3.5. Case Study 10: ArkaeVision

In a research study conducted by Bozzelli, Raia, Ricciardi, De Nino, Barile, Perrella and Palombini is shown that the ArkaeVision project aims to enhance the experience of Cultural Heritage by creating a more engaging and culturally-rich user experience through the development of a technological infrastructure. This system allows users to interact with Cultural Heritage, including virtual reconstructions of monuments and artefacts. ArkaeVision introduces a new communication model, blending game-like exploration in 3D environments with elements of digital fiction and engaging storytelling, applied to two case studies: the exploration of the Hera II Temple of Paestum with Virtual Reality (VR) technology (ArkaeVision Archeo), and the exploration of the slab of the Swimmer Tomb with Augmented Reality (AR)(ArkaeVision Art). By emotional engagement and gamification, ArkaeVision deepens the user interaction and understanding. The system also supports intuitive interactions by offering customised and inclusive experiences with advanced interfaces. Finally, the multi-user mode allows users to share their experiences within an immersive virtual environment.

Figure 22. The current Hera temple exterior (in Paestum) (Source: Bozzeli et al., 2019, p.15)

3.4 Identifying criteria according to which case studies will be presented and analysed

Following the presentation of the above mentioned case studies of using personal or multi-user VR technologies for presenting CH content, an attempt is made to analyse their implementation in terms of several of their characteristics, as criteria for this analysis: Numbers of users, objective of use, type of content, technological infrastructure, user interface, the extent to which they supported the editing of CH content, the quality of graphical representation presenter and the context within which this production was created. The table below summarises the analysis of these case studies according to their main characteristics:

	Number of Users		Functionality/Objective			Content			Technologies	Interface				Extent of Content Editing			Graphics' Quality			Context / Production	
Case Studies	Single User	MultiUser	Virtual Museum	Repurposing of	Edutainment	Artifacts	Buildings	Sites Landscapes		Immersive VR	Desktop VR	AR/MR	Other	None	Editing Manipulati	Composition with Other	Basic	Advanced	Photo-realistic	Academic /research	Commercial
Phygital Exhibition		X	X			X	X		Mozilla Hubs	X	X			X			X				
VIVE Arts	X		X	X	X	X				X								X			X
Museum of Other Realities		X	X			X				X								X		X	
Silk Road		X	X			X		X	Unity Photogrammetry	X		X			X			X		X	
Çatalhöyük VR		X	X			X	X	X	Unity	X					X			X		X	
Santiago de Compostela VR		X	X		X		X	X	VRML Java	X								X		X	
Beyond Matter		X	X			X			Mozilla Hubs	X					X		X			X	
ATON Framework		X				X	X		Node.js Three.js	X		X						X		X	

ArchiSearch		X	X			X	X		**web-based VR AI**	X				X							
Da Vinci Effect		X			X					X											
Museum of the Future		X	X		X	X	X	X		X					X						
Burns Beyond Reality		X		X		X	X			X										X	
Cultural Universe		X				X	X	X		X							x				
ChronoscopeVR	X		X		X	X	X	X		X				X			x				X
HeriVerse	X					X	X	X				X					x				x
BRIDGES		x		x	x	x	x		**Immersive Deck platform, real-time Holodec, Triple-TrackTM Software**	x		x			x			x		X	
The Lost Time	x			x		x	x	X		x				x					X		
The Restoration of Notre-Dame de Paris							x		**3D laser mapping/scanning**										X		

Underwater Malta	**x**		**x**			**x**			**photogrammetry**	**x**	**x**			**x**					**X**		
WWII Game: Defending the Island Fort	**x**				**x**	**x**	**x**	**X**		**x**				**x**				**x**		**X**	
CREATE Project	**x**		**x**					**X**	**Modelling-from-images technologies**	**x**					**x**		**x**			**x**	
AAlt-Segeberger Bürgerhaus Virtual Museum		**x**	**x**				**x**		**Terrestrial laser scanning, Digital photogrammetry, Unreal game engine**	**x**	**x**				**x**		**x**			**x**	
The Scottish Lewis Queen Chess Piece	**x**					**x**			**3D Printing, Haptic Device**			**x**			**x**						
The FIRB Project		**x**	**x**					**X**	**Laser Scanning, Total Laser Station, Computer Vision, GPS, GIS, Remote Sensing, Photogrammetry, 3D Panorama, 3D Computer Graphics**	**x**						**x**			**x**	**x**	
Ancient Via Flaminia Virtual Museum		**x**	**x**					**X**	**Total Laser Station, Laser Scanning, GPS, GIS,**	**x**					**x**			**x**			

									Computer Vision, Photogrammetry, Digital Photos from Aerostatic Balloon												
ArkaeVisio n	**x**	**x**	**x**					**X**	**3D Modelling, Unity Game Engine**	**x**		**x**				**x**			**x**		

From the analysis of the above-mentioned case studies that integrate cultural heritage content into virtual environments, we can extract a set of interesting initial remarks and "lessons learned". Firstly, we observe that all multiuser online virtual environments use basic or advanced quality graphics. Photorealistic graphics are used in single-user and offline virtual environments, as they cannot be fully supported by multiuser and/or online VR applications. Moreover, in most case studies users can virtually navigate inside cultural heritage sites and examine CH content from different angles. In some examples, users are additionally allowed to translate or rotate small-scale CH artefacts. However, more extensive interaction with CH items, including advanced manipulation, editing or composition with other types of content is uncommon. Additionally, cultural heritage content is usually displayed in its original context. It is rarely artistically reappropriated, critically reinterpreted or inserted into new contexts. In the majority of the presented cases, users can experience the virtual environments in immersive mode, using head-mounted displays. Some projects, also explore extended or mixed reality interfaces. Finally, in most of the projects, especially research-oriented ones, custom-made solutions have been developed in order to support the required functionality of the virtual environments. It is also important to stress that some of these VEs, based on third-party off-the-shelf platforms, such as Mozilla Hubs, are no longer accessible, after the closure of these platforms.

4 State of the art of XR interfaces used to interact with MUVEs

4.1 Introduction

Social Virtual Reality (VR) represents a significant advancement in digital communication, offering immersive environments for social interaction, education, and entertainment. Social VR enables users to interact in virtual environments using avatars and advanced interaction modalities. This technology has rapidly grown, driven by advancements in VR hardware and software. This sub-chapter examines the design strategies of social VR interfaces, the interaction modalities that enhance user experiences and communication methods and technological aspects and equipment that underpin effective social VR experiences, drawing from key research papers in the field.

The technological landscape of VR for cultural heritage applications, as far as interaction modes and modalities are concerned, has been rather aptly summarised in the following diagram by Bekele & Champion (2019, p. 4).

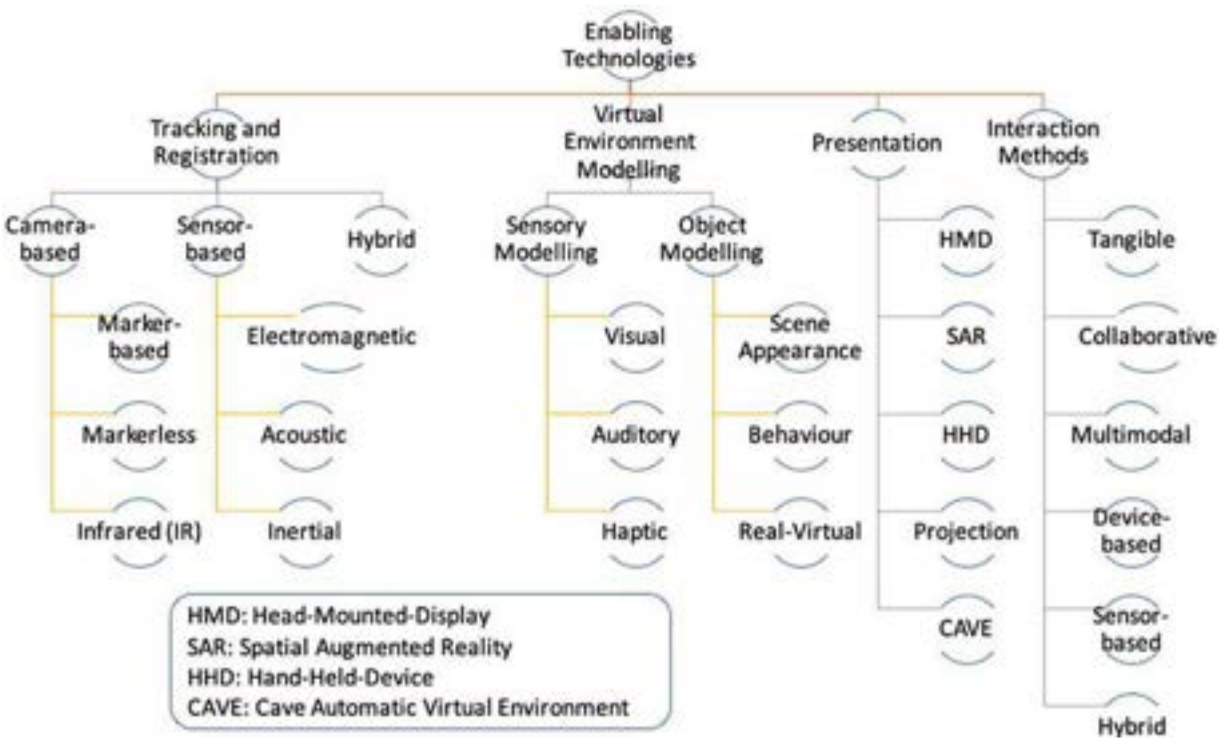

Figure 23. Technologies that enable immersive reality (Bekele & Champion, 2019, p. 4).

The authors note the potential of use-centred, personalised, and accessible content presentation through the use of virtual heritage, in the form of virtual reconstruction, simulation, or virtual museums. Their review used the following dimensions as criteria:

Support of user engagement by the technology used;

- Support for physical and virtual co-presence - in the authors' terms, "co-located" and "remote collaboration", respectively (Bekele & Champion, 2019, p. 5);
- Interplay among the users, the real ("reality"), and the virtual world ("virtuality").

It is worth noting that Bekele & Champion (2019, p. 6) view VR as potentially enabling remote collaboration, but regard co-located collaboration as 'irrelevant', since it is more suited to other forms of extended reality, such as mixed or augmented reality[17]. Depending on whether one regards VR as reliant on the use of HMDs, this view may be considered somewhat narrow - for instance, projection-based VR can be a viable alternative, especially in cultural heritage applications.

Cecotti (2022) views fully immersive VR as VR used with a head-mounted display (HMD); however, immersion may be regarded not as a discrete category, but as a continuum, and applications and systems may be positioned at various points along it - for instance, projection-based VR and desktop VR may be regarded as immersive depending on the interaction modalities and techniques they support.

Furthermore, Cecotti (2022) identifies eight requirements for the development of virtual heritage applications, i.e. virtual representations of buildings, sites, monuments, and other cultural content: (i) high geometric accuracy, (ii) capture of all details, (iii) photorealism, (iv) high automation level, (v) low cost, (vi) portability, (vii) application flexibility, and (viii) model size efficiency. Several of these requirements are related to display quality, which can be hypothesised (Li, Lin, & Tian, 2024) to be positively correlated with the experience of flow (Csikszentmihalyi, 2014) and user satisfaction in general.

Immersive VR may be instrumental in conveying the experience of a museum, since the sense of movement from one exhibit to another is a key part of the experience that cannot be accurately reproduced in desktop-based VR (Cecotti, 2022). This reasoning may be extended to all other types of cultural content which need to be experienced in a way that resembles perception of physical spaces or artefacts. Cecotti lists various applications available on Steam or on the Oculus Store (by July 2022) which attempt to leverage the spatial and immersive nature of VR - for instance, The Night Cafe: A VR Tribute to Vincent van Gogh transforms famous 2D paintings into navigable spaces that

[17] Bekele & Champion (2019, pp. 9-10) summarise their findings in a set of comprehensive tables. It may be necessary to broaden the view of what falls under the category of VR, as their view is rather narrow and prevents the use of technologies in ways that may enhance the experience of the users. Perhaps the most restrictive limitation of their view is the stipulation that VR rely mostly on single-user equipment, thus rendering on-site collaboration problematic at best.

may be experienced from various vantage points. Additionally, Cecotti highlights an important issue in the design and experience of VR for cultural heritage:

> *"The temptation to display a complete series of paintings, to show everything from an artist (e.g., all the variations of a painting, all the portraits, ...). This quest for completion and complete series cannot hold the attention of the ordinary visitor. After seeing the third or fourth example of a portrait, the user will lose interest and move onto a different activity. This element shows the importance of a museum curator, even within a VR environment, the same way that video games need game designers"* (Cecotti, 2022, p. 97).

4.2 Design Choices in Social VR

The design of social VR applications is categorised into the three following areas to ensure immersion and engaging VR experiences:

- Self-Representation: Avatars are the main aspect of Social VR applications, as they allow users to project their identity within the virtual space. Advanced tracking technologies can capture gesture, body movements and facial expressions, enhancing the avatar's realism, intensifying the embodiment (Handley, Guerra, Goli, & Zytko, 2022).
- Interaction Mechanisms: Interaction modalities used in Social VR applications, include haptic feedback, gesture recognition and spatial audio. These mechanisms contribute to the creation of a more intuitive and natural communication between users, as they provide a closer feel to a realistic interaction between people (Handley et al., 2022; Moustafa & Steed, 2021).
- Environmental Features: The setting of a Virtual Environment can vary, ranging from a realistic setting to a more abstract one. The design of these environments influences user engagement and interaction, providing context and enhancing the immersive experience (Handley et al., 2022).

Chong et al. (2022) conducted a systematic review of VR for cultural heritage practices, identifying the following design and development trends:

- Reconstruction and digitization of cultural content
- Optimization, so that VR applications can run on lower-end systems
- Preservation of content
- System design
- Presentation
- With respect to technology, the review by Chong et al. (2022) indicates the following motivations behind the reviewed studies:
- Promotion of high-quality user experience

- Promotion of technology
- Knowledge transfer (using XR technologies to facilitate learning)
- Performance - e.g. freedom of interactivity, effective visualisation methods, installations for public use, and technology assessment of various types of VR output

The authors note that, compared to other domains, VR for cultural heritage is characterised by a higher degree of complexity of the interactivity of inputs and outputs. Improved usability is a requirement, given that a large percentage of users of such applications come from a variety of backgrounds.

Kosmas et al. (2020) highlight the fact that cultural heritage needs to incorporate the tenets of universal access. Freeman & Acena (2021) provide examples of interviewed users with disabilities who perceive social VR as liberating, in the sense of allowing them to escape their physical environment, to which they are confined due to health issues. This is another argument in favour of equipping a VR system with a multitude of interaction modalities.

Furthermore, it is worth noting that virtual environments do not need to adhere to real-world conventions and limitations, and, in non-shared VR systems (i.e. systems in which users are not physically co-present during use), content may even be transformed or adapted to the needs, requirements, and desires of each specific user.

4.3 Communication in Social VR

Even in early research on social VR, it became evident that users adopt means of communication that at least partially resemble those typically employed in traditional settings (for a recent review, see Han & Bailenson, 2024). Furthermore, this tendency extends to the users' avatar and that of other users who populate a shared virtual environment; avatars need to incorporate nonverbal communication cues as much as hardware components need to be able to detect them for the experience of interacting in shared virtual environments to present a high degree of similarity to that of interacting in the real world. The interaction modalities a social VR system incorporates may affect the characteristics of the interaction among users. For instance, Herrera, Oh, & Bailenson (2018) report that users whose avatars did not map their physical movement tended to move their hands significantly less when interacting with another user, highlighting the importance of behavioural realism of avatars with respect to user behaviour in virtual settings. Similarly, according to a study by Aburumman et al. (2022), users tend to prefer interacting with avatars that nod over those that do not. McVeigh-Schultz, Kolesnichenko, & Isbister (2019) observed design choices that rely (among others) on embodiment, namely avatar affordances, locomotion modes (e.g. teleportation), proxemics and utilisation of personal space.

Freeman & Acena (2021) note that prior studies on social VR highlighted that this medium supports real-time full-body movement and gestures, and can thus mediate both verbal and nonverbal communication, as well as various forms of social activities. Fang et al. (2021) compared the use of various communication cues commonly used to initiate or terminate a conversation - namely changing head orientations, clapping hands, waving hands, moving closer to / away from the other person, verbal greetings, 'ice breakers' other than greetings (e.g. asking random questions), using closing words (e.g. 'goodbye'), going into a topic directly, and making random noises - between face-to-face and virtual interactions. They found substantial differences across the two modes; the most noteworthy difference was related to the directness of interaction: in the virtual setting, nonverbal cues (e.g. spatial proximity, making noise or employing other nonverbal auditory cues, etc.) were not used to the same extend; instead, verbal cues were preferred, resulting in a more direct and straightforward interaction. However, it could be argued that, notwithstanding these findings, improvements in interactive technologies that would render interactions in VR more similar to those observed in face-to-face situations would shift related trends towards simulating natural communication modalities.

Communication in Social VR applications is achieved through the following systems:

Telepresence Systems

According to Roth et al. (2019), telepresence systems are technologies based on multi-camera setups and RBG/RGB-depth sensing to capture and project a user's appearance and behaviour in both VR and AR environments. These systems work by tracking and mirroring the user's movements and gestures, enabling realistic interactions enhancing the immersion. However, the drawbacks that can be addressed are the following: a) The optical path between the user and the camera may sometimes be hindered by the HMDs, resulting in low quality replication of the facial expression and the user's gaze. b) The complexity of modifying the user's behaviour based on real-time point cloud data is a task not fully addressed yet. In the research mentioned above examples of telepresence systems are presented:

- Fuchs et al. (1994) introduced the concept of realistic telepresence systems using a multi-camera ("sea-of-cameras" approach), later enhanced by Maimone and Fuchs (2011) with multiple Kinect cameras.
- Beck et al. (2013) and Kulik et al. (2018) developed systems that support projection-based multi-user collaborative interactions, in both local and remote groups, by tracking the user's activity through multiple RGB-depth cameras.
- Otsuka (2016) developed MMSpace, a system that supports kinetic displays

that mirror the user's head position in group-to-group conversions, which appears to be more realistic than a static avatar.

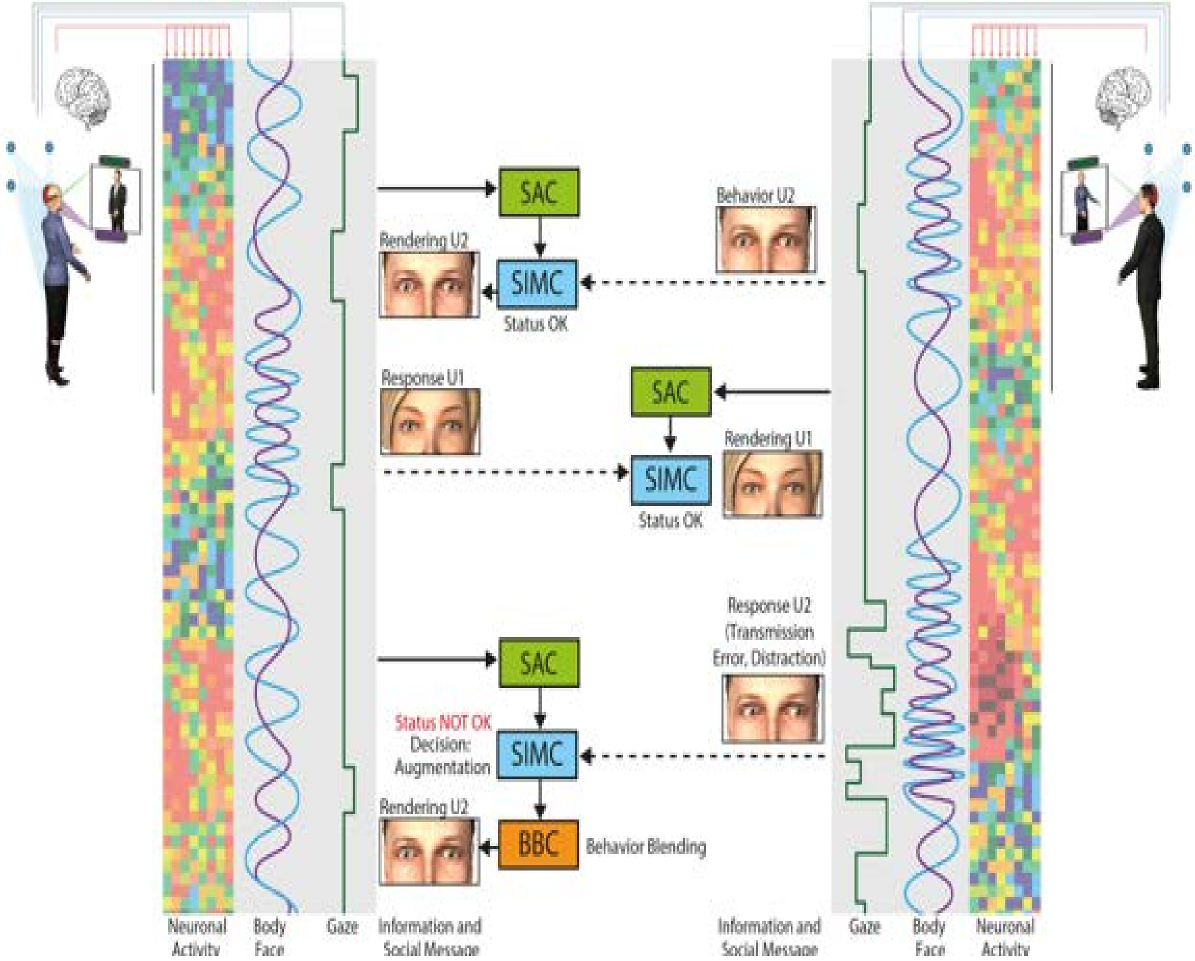

Figure 25. Augmentation Example (Gaze Focus) (Source: Roth et al., 2018, p. 5)

Avatar-Mediated Systems

According to Roth et al. (2019), avatar-mediated systems are platforms that enable users to utilise avatars and/or virtual characters to replicate human movements and behaviours. The advanced tracking technologies these systems use, capture facial expressions, gaze and body movements, replicating them through the avatars in the virtual environment offering the sense of realistic interaction. Avatar-mediated systems may not achieve the high realism of telepresence systems, but they offer the users flexible customization choices for avatars to better express the human behaviour.

In the research conducted by Roth et al. (2019) the InjectX prototype was presented. InjectX enables real-time, multi-user immersive interactions in virtual environments by tracking users' behaviours such as body motion, eye gaze and facial expressions of the lower face. The system supports status analysis, decision-making, behaviour blending and augmentation. InjectX was developed using Unity3D, Python, and TensorFlow for pattern recognition. The system can host any number of users as it is based on a client-server architecture and the Unity3D network API (UNet). Behaviour tracking data is pre-processed and applied to users' avatars through an exchange model layer, with continuous synchronisation of data across clients via UDP. The simulation is rendered on FOVE 0 HMDs, integrating FOVE 0 inertial measurement unit data with the positional tracking of the motion tracking system.

Communication Modalities

In Social VR applications both verbal and non-verbal cues are needed for an effective communication to be achieved. According to Moustafa and Steed (2021), users perceive interactions in social VR in a way that is similar to offline interactions, paying more attention to gestures and body movements. Non-verbal communication cues, such as facial expressions and body language, are crucial for users that want to convey their emotions accurately.

Multimodal interaction that goes beyond the 'usual' modalities of vision and audition has been explored - for instance, Karunanayaka et al. (2018) describe a system that produces and modifies thermal taste sensations on the users' tongue; Li & Bailenson (2017) describe an olfactory-based VR application.

Facial tracking

Comparing face-to-face and VR interaction, Rogers et al. (2021) found that users interacting with realistic motion avatars tend to rate the experience in a way that is somewhat similar to face-to-face interaction. Furthermore, eye contact was positively associated with enjoyment, closeness, and comfort.

Haptic Feedback and Immersion

Vaz, Fernandes, & Veiga (2018) refer to a number of relevant projects that feature tangible interaction. In addition to enhancing the museum experience, haptics can be useful in providing a more complete communication among users of social VR systems. The feeling of touch in Social VR applications is achieved through haptic feedback devices such as vests and gloves. Through the tactile sensations resulting from the interaction with virtual elements, the realism and immersive experience are enhanced. This way the gap between virtual and physical worlds can be bridged (Mulders & Zender, 2021; Ruiz, Molina-Espinosa, Magana, & Benes, 2022).

The importance of virtual touch for reversing the trend of disconnecting communication from its physical components and for preventing adverse psychological states on the part of the user is highlighted in a review by Della Longa, Valori, & Farroni (2022). Immersive virtual reality offers the possibility of embodied interaction (in the sense of body location, agency, and ownership). Virtual bodies also contribute towards the establishment of co-presence, i.e. the sense of being in the virtual environment with someone else. Hoppe et al. (2020) showed that the sense of touch (in this case via an artificial hand) may increase the perception of human likeness of artificial virtual agents. Specifically, the perception of agents was positively influenced with respect to perceived agency, perceived co-presence, and experienced sense of embarrassment. In the words of Della Longa, Valori, & Farroni (2022, p. 7), "affective touch is fundamental in giving life to the virtual experience, as it is closely linked to emotions, in a mutual influence that nurtures social encounters". However, the authors note that, in some cases, the high degree of interaction fidelity provided by touch input and output and the resulting high degree of immersion, may in turn lead to users struggling to differentiate between the virtual and the real. Furthermore, the provision of touch when touch is not desired may lead to negative effects - see Slater et al. (2020) for a relevant discussion, as well as Maloney, Freeman, & Robb (2021) for a discussion on ethical aspects of future research on social VR.

Spatial Audio

Spatial audio systems allow users to experience sound in a more realistic way since they simulate direction and distance of sounds to mimic the real-world experience. The sense of presence in the virtual world is enhanced and the immersion deepens. These sound systems appear especially useful in group conversations and activities designed for multiple users (Ruiz et al., 2022).

4.4 Multimodal Human-Computer Interaction

The technological advancement in VR interaction systems, such as improved Head-Mounted Displays (HDMs), motion controllers and haptic devices has offered users the chance to communicate both with the environment and each other in more natural, effective and intuitive ways (Mulders & Zender, 2021). Nonetheless, limitations do exist - for instance, there is room for improvement regarding the display quality (resolution, refresh rate) of HMDs; furthermore, interaction between users and virtual objects remains a challenge (Kyrlitsias & Michael-Grigoriou, 2022).

Vaz, Fernandes, & Veiga (2018) refer to various art projects, museums, and exhibitions that utilise multi-touch display and projection technology; they also list a number of VR projects in which users are not limited to simply looking around, but they can move freely as well (this ability to move around is considered a necessary characteristic of VR, as opposed to 360-degree immersive visual experiences). Furthermore, they list several implementations in which beacons (for location tracking) and wearable equipment (for various types of measurements) are used.

In the research conducted by Ruiz et al. (2022), great emphasis is given on the need of multiple interaction modalities in Human-Computer Interaction (HCI). This way more immersive and engaging applications can be developed. Visual, auditory and haptic feedback systems are required to create a richer user interaction experience in Social VR applications.

Olin et al. (2020) present a VR system that supports cross-collaboration through different devices, namely an HMD and a mobile touchscreen device. Their findings indicate that handheld users managed to attain a high degree of immersion and presence despite the non-immersive nature of their device (compared to an HMD). The authors evaluated the interaction patterns by using two scenarios: conversation and collaborative building (joint construction of an abstract object); they observed that, in the former scenario, handheld users assumed similar positions as they would in the real world. Furthermore, they tended to look at the other participant much more than HMD users, who rarely did so. Also, handheld users exhibited stronger movement patterns compared to HMD users in the collaborative building task. Another interesting observation was that leadership was not related to the degree of immersion.

Olin et al. (2020) highlight a number of important points when it comes to designing collaborative virtual experiences involving handheld devices. A virtual experience through an HMD allows for spatial cues similar to those normally perceived in the real world, thus facilitating spatial awareness. On the contrary, when using handheld devices, such cues are either absent or diminished (there is no depth perception / stereoscopic view when experiencing space through the screen of a handheld device). Another challenge when designing virtual experiences for handheld devices is related to the method of navigation, which is bound to be less natural (compared to that of HMD users) due to the lack of positional tracking. The study revealed the users' preference for moving by means of a 'pinching / spreading' two-finger gesture (similar to the gesture typically used for zooming in / out), and rotating via the smartphone's gyroscope (including switching between absolute and relative gyroscope mode).

With respect to the conversational scenario, Olin et al. (2020) note that handheld users tended to assume a face-to-face configuration when the line of sight between the participants was unobstructed; when view was obstructed, handheld users either assumed a face-to-face configuration after positioning themselves so as to overcome the visual obstruction, or opted for other configurations, such as corner-to-corner or side-by-side[18].

[18] The authors refer to "F-formations", using the framework of Ciolek & Kendon (1980), with adjustments by Dim & Kuflik (2013), to describe the spatial arrangement between participants. Furthermore, the authors acknowledge a limitation in their study: participants were recruited in pairs who knew one another beforehand.

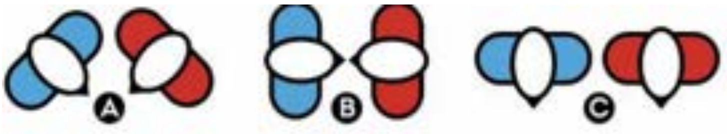

Figure 25. Three common configurations between two participants: (A) corner-to-corner, (B) face-to-face, (C) side-by-side (Olin et al., 2020, p. 114).

Olin et al. (2020) arrive at eight design considerations related to cross-device collaboration in social virtual environments. While all of them are important, some of them are particularly relevant to the interaction techniques employed. Specifically, the authors encourage designers of such systems to support non-verbal communication by providing appropriate interaction methods (such as gestures, body posture, and viewing direction). Furthermore, adequate field-of-view (whether using an HMD or other devices) is necessary for accurate and consistent distance perception so as to avoid invasions of personal space. These recommendations highlight the fact that research on 'traditional' face-to-face communication between two or more actors remains relevant when designing social virtual experiences. The importance of incorporating communicational aspects of space (in particular, the spatial arrangement and configuration of the participants) in the design of XR experiences is also highlighted by Schwajda & Anthes (2022) and Pathi et al. (2019). Kyrlitsias & Michael-Grigoriou (2022) note that immersive virtual reality and associated technologies provide a fertile ground for replicating social experiments with a high degree of ecological validity, further underlining the (ideally) close relationship between established theory on social behaviour and interaction and technological applications. Furthermore, an accurate representation of human actions - i.e. body and eye movement, facial expressions - on avatars / virtual bodies is important for inducing the sense of body ownership, as well as for communication with other users in shared immersive environments (Kyrlitsias & Michael-Grigoriou, 2022, p. 5).

4.5 Technological infrastructure for Social VR

Immersive Social VR often involves tracking of body movements in order to provide a more holistic experience (Interaction Design Foundation, 2023). In general, there are two main modes of delivery for immersive virtual reality: Head-Mounted Display (HMD) and projection-based (Slater & Sanchez-Vives, 2014). Non-immersive forms of VR (e.g. VR-enabled chat / messaging applications, multiplayer games, etc.) may be delivered using conventional equipment, such as a typical personal computer or mobile device. Typically, modern commercial social VR platforms incorporate high-fidelity 360-degree content and six degrees of freedom, while allowing for a multitude of verbal and nonverbal communication means (Maloney, Freeman, & Robb, 2021). This results in a richer communication experience[19] while adhering to accessibility standards and recommended practices.

Although employing interaction devices that support a large number of degrees of freedom often results in performance improvements, Liarokapis et al. (2017) argue in favour of decreasing the number of degrees of freedom if the task at hand allows it, in an attempt to make the interaction easier to understand by a wider audience. Thus, the authors suggest the utilisation of hybrid interfaces, which they define as combinations of 3D input devices with a 2D device.

Head-Mounted Displays (HMDs)

HMDs are the primary interface for accessing social VR environments. They provide immersive visual experiences by encompassing the user's field of view with high-resolution displays. Modern HMDs are equipped with advanced sensors that track head movements, enabling users to look around and interact with the virtual environment naturally (Handley et al., 2022). HMDs can be tethered or standalone (Angelov et al., 2020); the latter tend to be better in terms of ergonomics, since they do not require cables that may hinder movement - thus, they may be more suitable for applications that require a high degree of mobility[20]. On the other hand, such HMDs rely on their onboard hardware for content rendering, which may not always be adequate, and the same applies to battery power. Tethered HMDs rely on the computer's processing power and are thus more suited for demanding applications.

The screen-door artefact (the pixel contours forming a visible grid) is present to a lesser or greater extent in all HMDs due to the small distance of the screen to the users' eyes, but can be mitigated through high pixel density. Additionally, the perception of the image presented to the users as natural tends to increase as the field of view increases. It should be noted that, in order to increase field of view, it is necessary to increase screen size, which may adversely affect the screen-door artefact (Angelov et al., 2020). Another important characteristic of HMDs is their refresh rate; generally, the higher, the better for performance, presence, and the quality of the user experience (including absence or reduced severity of motion sickness symptoms). While it is not uncommon to see monitors (especially high-end ones intended for gaming) achieve a very high refresh rate (over 100Hz), HMD refresh rates tend to be more modest, at least presently. Still, they are

[19] Comparing social VR to traditional virtual worlds, the authors note that communication in social VR is currently not archivable (Maloney, Freeman, & Robb, 2021). This is partly due to the interaction modalities supported in modern social VR, which attempts to simulate traditional nonverbal communication. Archiving such interactions would rely on a commonly agreed-upon logging protocol that would encompass a wide variety of intentional and unintentional, verbal or nonverbal, interaction cues.

[20] VR glasses are a subtype of standalone HMDs: they are a set of lenses that need a smartphone to serve as display and rotation sensor, but their lack of tools for interaction with the content may result in a reduced sense of presence. Also, they often lack positional tracking, which places limits on what the users can do.

consistently over 75Hz, with the Valve Index achieving a maximum refresh rate of 144Hz, a performance that is on par with the aforementioned monitors.

While positional tracking is at present considered a basic requirement for modern HMDs, some (like the Valve Index) also provide finger tracking. This can allow for richer user interaction when fine-grained manipulation of objects is involved. In addition to tracking, weight and form factor are important in an HMD, as they directly affect the user experience, especially during prolonged use[6].

Motion Controllers

The possibility of utilising kinesics when interacting with other users in a social VR setting brings immersive VR closer to face-to-face interaction and is dependent on appropriate body tracking hardware. In many cases, while speech tends to be the predominant mode of communication among social VR users, the users in question appreciate the system's ability to support body movement as an input signal, enabling them to interact (e.g. via body language) with other users who cannot speak for whatever reason (Freeman & Acena, 2021).

Motion controllers allow users to interact with the virtual environment through hand movements. These controllers are equipped with sensors that track the position and orientation of the user's hands, enabling precise manipulation of virtual objects. Advanced controllers also include haptic feedback to enhance the tactile experience (Ruiz et al., 2022). Another category of motion trackers uses the entire body as input (full-body motion tracking), e.g. motion capture suits. While accurate, such systems are often expensive, which prevents the majority of end users from being able to use them. Using more than one tracker for various body parts may result in an approximation of body tracking which is less accurate, but more affordable and easier to set up and use by comparison (Kyrlitsias & Michael-Gregoriou, 2022).

Regarding locomotion, a standard solution often employed is teleportation, i.e. pointing at a location with a handheld controller and, upon pressing a button on the controller, moving the camera at that location. This solution was used by Soto-Martin, Fuentes-Porto, & Martin-Gutierrez (2020) in their virtual reconstruction (developed in the Unity game engine) of the church of St. Augustine in the city of San Cristóbal de La Laguna Tenerife, Spain. Regarding the efficacy of this locomotion technique, it may be said that, while potentially limiting the users' freedom of movement, it may be advantageous from the point of view of motion sickness, as it is often not accompanied by rapid turns and movements that tend to contribute to the appearance of adverse symptoms and effects.

Reimat et al. (2022) describe a cultural heritage experience using social VR. Three Microsoft Kinect sensors were used alongside an HTC Vive Pro headset for interaction and navigation in virtual space. Users can freely interact with a specific exhibit (a costume) and take part in a curated tour. The system supports co-presence for multiple users.

Haptic Devices

Haptic devices, such as gloves and vests, provide tactile feedback that simulates the sensation of touch. These devices are crucial for enhancing the realism and immersion of social VR experiences. By providing physical sensations that correspond to virtual interactions, haptic devices enable users to feel the virtual environment, making interactions more engaging and intuitive (Mulders & Zender, 2021). Perret & Vander Poorten (2018) classify haptic devices in three broad categories: (i) gloves, i.e. hand-shaped garments made of flexible fabric, (ii) thimbles, i.e. devices involving actuators attached to a fingertip, and (iii) exoskeletons, i.e. articulated wearable devices capable of transmitting force. The authors provide a review of existing haptic devices from all three categories.

Haptic feedback is regarded as a useful tool in bridging the gap between the real and the virtual; being able to touch virtual artefacts renders the simulation of the virtual museum more lively and intuitive. To that end, dedicated devices specifically designed to utilise touch ad input and provide tactile output (e.g. force feedback) have been used in such settings - for instance, the Novint Falcon to simulate the shape, texture, and material of virtual artefacts (Arnab et al., 2011).

Auditory interaction and Spatial Audio Systems

Sound is an interesting choice of interaction modality, since users (ideally) do not need to learn potentially complex interaction methods, since they could simply talk to the computer; the same applies to users who are visually impaired. Of course, the current situation in speech recognition and comprehension is still not adequately accurate for general usage of speech as input (the larger the domain of discourse, the less the degree of recognition accuracy). Regarding using sound as output, text-to-speech synthesis can be an affordable and easy to implement solution, but it tends to suffer from a low degree of naturalness (e.g. robotic voice); though more naturally sounding voices are now available, the intonation and overall speech patterns of text-to-speech system output still lags behind what might be considered natural by the wider audience. The alternative of employing voice acting talent is still a viable option (though the increase in the usage of generative AI may soon make this practice redundant). Nonetheless, Liarokapis et al. (2017, p. 381) provide a number of examples of interactive applications that employ sound as their primary modality.

Spatial audio systems use advanced algorithms to create a 3D sound environment that mimics how we hear sounds in the real world. These systems are essential in social VR for enhancing the realism and immersion of the virtual environment. They help users locate sounds in space, which is crucial for effective communication and interaction (Ruiz et al., 2022).

Computer vision

Computer vision is an interesting choice when it comes to positional tracking, since it can be non-intrusive (in the sense of allowing untethered interaction) and accommodate a large number of potential users and/or spectators, who may also interact with one another. Zabulis et al. (2013) describe such a system that utilises several cameras in front of a large screen. QR codes or other visual information is also a plausible choice for indoor position tracking.

Brain-Computer Interfaces

An HMD can be regarded as a good choice for mounting unobtrusive electro-encephalography [EEG] sensors (Tremmel et al., 2019). A non-invasive BCI can be a viable option for simple interactions in some cases, but they tend to suffer from various problems, mainly having to do with detection accuracy (at least in the lower, non-medical end of the spectrum), that render their effective use somewhat problematic. Still, they can accompany and supplement other interaction techniques, for instance by increasing the total number of degrees of freedom in a way that does not make things more complicated for other methods (Liarokapis et al., 2017) Additionally, BCI can be suitable in accessibility-related use case scenarios.

A BCI-based VR setup is based on software that records and classifies brain activity. From the point of view of hardware, it is important to couple the BCI device with the VR headset (if one is used) to avoid unnecessary delays in the communication between the two subsystems; if users are to move around, the use of active electrodes is recommended to avoid movement artefacts (Lotte et al., 2013). Various early applications combined VR with EEG for movement control, the general operating principle being the system training on the users' brain activity pattern, resulting in the users being able to navigate virtual spaces after this training period (Lotte et al., 2013).

Lotte et al. (2013) highlight the issue of user fatigue as a result of the need for continuous mental activity to navigate the virtual world. A potential solution is shared control: users select (via mental imagery) one from a small number (e.g three) classes in order to indicate specific navigation points, and the system 'drives' them there. In this manner, users are spared the low-level movement and locomotion details. A related application in which users are asked to move an object by 'imagining' the motion is described by Lotte, Renard, & Lécuyer (2008). Mental imagery seems to be suitable for locomotion but not so much for selection tasks due to the small number of available classes when using the former method. Evoked potentials are a much more suitable method if selection is required (Lotte et al., 2013).

Apart from its potential use as an interaction method, BCI can also be used for evaluation purposes. Škola et al. (2020) concluded that the use of EEG does not detract from the overall experience of using immersive VR.

4.6 Techniques of integrating facial and gesture recognition in XR aspects of MUVEs (EV)

4.6.1 Introduction

Facial and gesture recognition and tracking technologies allow to accurately capture and recreate users' facial expressions and body gestures. It is important to start with an accurate definition of each technique and to distinguish recognition and tracking methods properly.

Facial recognition is a technology that identifies a person by analysing and comparing patterns based on their facial features. It is based on capturing an image or video of a person's face, extracting unique facial features (eg. the distance between the eyes or the contours of the face), and comparing these features with a database of stored images to find a match. In multi-user virtual environments, facial recognition technology can be used to create personalised avatars or authenticate users joining experience.

Gesture recognition is the technology that interprets human body movements, particularly hand and arm gestures, as input commands. By analysing the position, orientation, and motion of the body, gesture recognition systems can identify specific gestures, such as waving, or pointing, and translate them into actions or commands within a virtual environment. This allows users to interact with virtual environments more naturally and intuitively.

Facial tracking refers to the continuous monitoring and analysis of a person's facial movements in real-time. It tracks changes in facial expressions, head orientation, and other dynamic facial features over time. This data can then be used in virtual environments to replicate the user's real-time expressions and movements using virtual avatar. It increases realism and enables more expressive interactions.

Gesture / body tracking is the process of continuously monitoring and following the movement of a user's body, hands, or other parts over time. It ensures that the system accurately detects and responds to the user's gestures as they move within the virtual space. Gesture tracking is essential for smooth, real-time interaction in virtual environments, enabling users to perform actions and navigate the environment using their own physical movements.

According to the definition above, recognition techniques are focusing mostly on the process of detecting and classifying particular facial expressions or gestures making them an input into the system. Tracking techniques extend this single detection process into continuous monitoring of the person's facial and body movements enabling transferring them onto an avatar, that is virtual representation of the user in MUVEs.

4.6.2 Benefits of using facial and gesture recognition and tracking

Facial and gesture recognition and tracking technologies are essential elements of Multi-User Virtual Environments (MUVEs) enabling more natural, immersive, and interactive experiences for the users. They also enable real-time, non-verbal communication, critical for effective social interaction and provide the ability to enhance the sense of presence and realism which is especially important in the context of experiencing cultural heritage. Gesture recognition simplifies navigation in the MUVEs and control of the avatar, allowing users to interact with the virtual environment in a much more intuitive way. Overall, facial and gesture recognition and tracking bridge the gap between the physical and virtual environment, making interactions more engaging, accessible, and personalised.

Facial and gesture recognition used in Multi-User Virtual Environments (MUVEs) provide unique benefits in the context of cultural heritage, enhancing the education, preservation, and experiencing of cultural artefacts and practices. Here are some key benefits:

- **Enhanced Immersion, Embodiment and Presence**. By using facial expressions and body gestures users interact with both virtual environments and each other in a more natural and intuitive way. This makes users feel more physically present and helps them focus on the content instead of technological aspects of the experience. Real-time facial expressions and gestures mapping onto avatars, allows users to express their feelings and emotions which can be used as an input for the virtual experience, strengthening the story and the message. This benefit is clearly confirmed by research conducted at Department of Digital Media, Ajou University in Republic of Korea by Haejung Suk & Teemu H. Laine. (2024)

- **Accessibility and Inclusivity for Cultural Heritage.** Gesture recognition allows for hands-free control and navigation within the virtual environment, which is beneficial for users with physical disabilities or those who find traditional input methods challenging to use. This approach is confirmed in the research “Effects of interacting with facial expressions and controllers in different virtual environments on presence, usability, affect, and neurophysiological signals” conducted by the team led by Arindam Dey from the University of Queensland and Dr. Mark Billinghurst from the University of South Australia (Arindam Dey et al., 2022). Facial recognition enables the creation of personalised avatars that resemble the user’s real appearance. It promotes inclusivity and identity representation within the virtual space, which is especially important when cultural heritage is experienced by a group of users simultaneously. It fosters communication among the users and makes it more emotional.

- **Immersive Educational Experiences.** A multi-user virtual environment's ability to recognize and respond to individual users' expressions and gestures allows it to offer much more personalised experiences. Virtual characters, as a part of cultural heritage experience, can react differently based on the user's mood or actions, creating a more dynamic and interactive environment for education and a deeper emotional connection between the user and the subject matter. These technologies also allow users to engage in traditional moves, dances or rituals by mirroring the gestures of virtual instructors. Analysis of users' emotions, may also help customise experience to improve its effectiveness and level of engagement. Similar concept was successfully validated in the research conducted in a more traditional e-learning environment (Daouadji & Bendella, 2024).

- **Preservation of Cultural Practices.** Capturing traditional gestures and expressions can digitally preserve traditional dances, rituals or expressions that are crucial to cultural heritage. By recording and accurately reproducing these gestures and expressions in virtual environments, these practices can be secured for the future generations. Facial and gesture recognition and tracking can help recreate historical personas, bringing them to life in virtual environments. This allows users to interact with virtual representations of important cultural icons in a way that is both engaging and educational.

4.6.3 Review of existing techniques and hardware technologies

Integrating facial and gesture recognition and tracking in MUVEs involves using a combining of various hardware and software technologies. To achieve proper results for particular virtual experiences it is important to select the most appropriate ones. To effectively select them for particular Multi-User Virtual Environments supporting digital representation of cultural heritage it is important to provide structure and categorization. Here is a brief review of existing face and body tracking solutions.

Facial recognition and tracking

Facial recognition and tracking rely on advanced algorithms and optical hardware, ranging from consumer-grade cameras to specialised sensors. The availability of powerful hardware tools makes it possible to implement facial recognition in a wide range of applications, considering different sets of requirements and budgets:

- Webcams and Smartphone Cameras are commonly used for facial recognition and tracking, especially in low budget consumer applications. These kinds of devices capture video that is then processed by dedicated software. Examples include cameras on devices like Apple iPhones[21] or high-quality webcams like Logitech

[21] Apple iPhone | https://www.apple.com/iphone/

C920[22]. They provide good image quality but they provide poor results in low light conditions.

- Infrared (IR) cameras are often used in facial recognition systems instead of regular cameras, particularly in low-light conditions. They work by capturing infrared light reflected from the face, allowing for accurate recognition even in the dark. They may be used in various scenarios and in combination with other technologies. The Apple TrueDepth camera system creates the 3D representation of the face using a combination of infrared camera and structured light scanning.

- Depth-sensing cameras can be also used to detect the face by building a 3D model of the user's face. Example may be a Microsoft Kinect[23] that is using a combination of infrared camera, RGB camera and depth sensor to detect and track face in real time.

- Combination of camera-based eye-tracking and mouth-tracking may be used in scenarios when the face is partly covered and not fully visible for a single camera. This scenario is especially relevant for Virtual Reality Goggles that are strongly covering the face of the users. HTC Vive[24] is a great example of a complete solution in that area. Full face representation is delivered thanks to dedicated infrared camera-based eye-tracking technology and additional mouth tracking sensor.

As all face tracking systems are visual it's sometimes useful to support them with facial detection and tracking adding physical markers on the face using colour that is contrasting with the colour of the user's skin.

Gesture recognition and tracking

Gesture recognition and tracking is enabled by a bit wider set technologies as working with the entire body allows us to use not only cameras but also additional markers and sensors that we can perform additional measuring and provide data.

- Camera-based motion capture systems are one of the most commonly used in professional settings. Correct capture of human body motion requires using one or more cameras looking directly at the user and using specialised software to convert video frames to body rigs. Infrared cameras are often used with support light-reflecting markers to achieve higher accuracy and less artefacts. Great example of a professional solution for camera-based motion capture is Optitrack[25]. With the advent of AI we can also see much more accessible solutions. Platforms like

[22] Logitech C920 webcam | https://www.logitech.com/pl-pl/products/webcams/
[23] Microsoft Kinect | https://learn.microsoft.com/en-us/windows/apps/design/devices/kinect-for-windows
[24] HTC Vive | https://www.vive.com/eu/
[25] Optitrack | https://optitrack.com/

MoveAI[26] or Kinetix[27] provide a decent body movement tracking using a single smartphone camera.

- Radio-based motion capture systems replace camera setup and reflective markers with radio-based sensors that are placed on the human body including hands, arms, legs, head and torso. They use inertial sensors like gyroscope and magnetometer to calculate body movement in real time and they send measurements to the central computing unit. Rokoko[28] or Movella Xsense[29] are great examples of this kind of solution on the more professional end of the scale. Sony Mocopi[30] or Pico Trackers[31] are cheaper solutions. Compared to camera-based solutions they do not require dedicated space covered by cameras and they are much more flexible. These suits can be also combined with Virtual Reality Google providing very deep immersion in Virtual Environments.

- VR Equipment is another method for gesture recognition and tracking. Both goggles and controllers, that are parts of VR setup, are powered by dedicated inertial sensors that allow tracking of the head and hands movement. Thanks to advanced algorithms they can also calculate upper body movement in real time. Headsets like HTC Vive[32] or Meta Quest[33] provide very high-quality results based on inertial sensors but due to the progress of vision-based systems that are both moving towards camera-based hand tracking supported by predictive algorithms. This move allows tracking not only arm movement but hand gestures.

4.6.4 Review of existing techniques and software technologies

Face and gesture recognition and tracking requires dedicated software capable of taking data from hardware described in the previous section and converting it into proper human body and facial rig. Below are described the most popular options that can be used to perform this task:

Apple ARKit and ARCore are one the most popular software solutions respectively for iOS and Android mobile platforms, natively provided by the operating system creators. They take advantage of deep system and hardware integration delivering great tracking results for both face and gestures. On the higher level they are integrated into the game engines

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[26] MoveAI | https://www.move.ai/
[27] Kinetix | https://kinetix.tech
[28] Rokoko |https://www.rokoko.com/
[29] Movella Xsense | https://www.movella.com/products/xsens
[30] Sony Mocopi | https://electronics.sony.com/more/mocopi
[31] Pico Trackers | https://www.picoxr.com/global/products/pico-motion-tracker
[32] HTC Vive | https://www.vive.com/eu/
[33] Meta Quest | https://www.meta.com/pl/quest/

like Unity 3D[34] or Unreal Engine[35] which provides great tools to create experiences in virtual environments.

- MediaPipe[36] library currently owned by Google provides great support for flat video-based tracking of both face and the body. Commonly used on PCs in combination with webcams.

- Banuba[37] provides proprietary face and gestures tracking capabilities available on a wide range of platforms including mobile and PCs. It's great way of introductions Augmented Reality features to applications with a very low effort

- Kinetix[38] is a software solution for converting flat 2D video recording into body animations based on humanoid rig. This solution is very convenient to be introduced on mobile and PC based platforms allowing users to create custom moves and emotes.

- MoveAI[39] allows for camera-based motion capture based on recordings or real-time. It allows the use of multiple cameras for capture which strongly improves the quality of delivered animations.

- Avatary Studio[40] is a universal facial animation solving software. It processes video from various cameras, animates a wide range of facial rigs, and supports mainstream DCC software.

- Face Wear[41] is a facial motion capture hardware and software combining cutting-edge technology and intuitive artist-friendly workflows to help professional animators accurately capture facial performances and create believable facial animation quickly and reliably.

- Cascadeur[42] is AI based solutions helping to smooth out animations by rendering intermediate animation frames between the body poses. Thanks to advanced machine learning and inclusion of physics it provides very good results.

[34] Unity 3D | https://unity.com/
[35] Unreal Engine | https://www.unrealengine.com/
[36] MediaPipe | https://github.com/google-ai-edge/mediapipe
[37] Banuba | https://www.banuba.com/
[38] Kinetix | https://www.kinetix.tech/
[39] MoveAI | https://www.move.ai/
[40] Avatary Studio|https://www.facegood.ca/AvataryStudio
[41] Face Wear| https://facewaretech.com/
[42] Cascadeur | https://cascadeur.com/

4.6.5 Opportunities and Limitations of Current VR Technology

The current state of VR technology offers numerous opportunities for enhancing social VR experiences. The integration of advanced tracking and haptic feedback technologies allows for more realistic and immersive interactions. Additionally, the development of volumetric video and real-time 3D video capturing technologies enables more lifelike representations of users and environments (Mulders & Zender, 2021; Handley et al., 2022). Use of VR technology can be also extended with elements like sound, narration, and interactive elements to tell the story of cultural heritage sites with the support of multi-sensory storytelling (Kun Lyu et al. 2024). This creates an immersive experience, enhancing emotional connections with the past and making cultural history more engaging and memorable. Cultural heritage preserved using immersive technologies offers much more than just passive observation. It enables a more active approach, where experiential learning is used (Oladokun et al. 2024).

Despite the advancements, there are still limitations to current VR technology. To fully utilise their potential in XR experiences, it is important to consider the right set of tools enabling facial and gesture recognition and tracking. The following factors should be considered when planning and designing immersive experience in MUVEs:

- Distribution platform. It is important to consider both hardware and software distribution platforms. Depending on the selection, designed experience may be more (eg. smartphones) or less (eg. VR headset) accessible for the users. It is important to consider that currently offered VR headsets rarely provide build-in technologies for face tracking. It's often required to equip headsets with additional 3rd party devices. Body tracking is more popular but also often requires additional sensors.

- Number of users participating. This factor is especially important if we decide to use less accessible equipment like motion capture suits or VR headsets. These kinds of devices require additional assistance when used. It is important to perform an introduction at the beginning, explaining the way a particular device works as well as covering limitations and safety guidance. In addition we need to consider maintaining hygiene safety when the same devices are going to be used by various participants. Higher number of participants in both remote and stationary setups required much more powerful server-based infrastructure and network bandwidth to avoid delays in interactions.

- Type of content (real-time or prerecorded). When creating XR experience in MUVEs we may decide to incorporate both real-time and pre-recorded content. It is especially important in experiences like concerts or a theatre performance where facial and body movement plays a significant role. Real-time setup is much more complex and vulnerable as it requires few different systems working together to capture and deliver tracking results to immersive environments. Pre-recorded content can be easily controlled and delivered but does not provide the ability to react to real-time interactions from participants. On the other hand it allows higher quality thanks to post production and use of AI based tools like Cascadeur.

- Accessibility and discomfort. It remains a challenge, as not all users can comfortably use VR equipment due to physical or cognitive limitations (Mulders & Zender, 2021; Moustafa & Steed, 2021). Alongside issues such as latency, limited field of view, a very important limiting factor is motion sickness. It negatively impacts the user experience of immersive technologies. In some instances, motion sickness can be ameliorated or prevented by improving the hardware - e.g. providing a higher refresh rate and resolution, a wider field of view, more accurate tracking, and even increasing processing power to avoid rendering delays and/or display artefacts such as tearing. However, innate propensity for nausea and dizziness is also a factor, and one that cannot be easily countered save for the gradual adaptation of the users to the stimulus (a process similar to how one gets accustomed to, and eventually may overcome, seasickness).

As a concluding remark, with regards to the potential modalities for interacting with multi-user virtual environments, an overview of existing relevant technologies indicates that it is currently possible to utilise a multitude of devices spanning a wide spectrum of interaction modalities in order to design and implement immersive experiences. These experiences can feature interaction that resembles face-to-face communication by allowing for the utilisation of nonverbal cues when interacting in the context of a social VR platform. However, more research is needed in order to highlight the ways in which such a complex interaction can be effectively supported by existing technology in a way that may be expected to enhance the User Experience of social immersive VR. Regarding existing widely available hardware solutions for social immersive VR, it may be noted that the latest HMDs support a greater resolution and refresh rate while featuring a wider field of view that often exceeds 100 degrees. Thus, the risk of motion sickness has been significantly mitigated. Furthermore, current-day HMDs are nowadays much faster and easier to set up by the end user, which increases the overall ease of use of immersive VR applications. More advanced interaction modalities are available by using appropriate equipment (e.g. BCI); however, further examination of the ways in which these disparate technologies can be integrated is necessary.

5 Integration of IMPULSE with existing content aggregators

While one of IMPULSEs objectives is to enhance the accessibility and discoverability of digital cultural heritage assets to be presented via XR technology, our focus lies on fostering diverse narratives and audience engagement approaches: how do we access existing cultural heritage assets, and what is the state-of-the-art to query, find and use repositories and databases of assets for practitioners such as game developers, filmmakers but also for GLAM to upload, sort and refine their digital assets?

In this chapter, we summarise our exploratory research into open databases for and of cultural heritage. We provide an overview of the advantages and limitations of current databases and dive deeper into the APIs of Sketchfab and Europeana to examine their potential for an integration into IMPULSE's pilots.

Key findings reveal significant challenges in the digital cultural heritage ecosystem, including repository fragmentation, heterogeneous metadata standards, and varying degrees of data accessibility (and therefore discoverability). The research uses a comparison of API features to analyse search criteria and filtering choices and how these can de- or increase the effectiveness of aiding content exploration and retrieval.

Among the platforms available for such uses, the aggregators Sketchfab and Europeana stand out as major cultural heritage asset hubs. Sketchfab is particularly strong in hosting and displaying 3D models and comes with tailored filters for 3D content; on the other hand, Europeana offers a robust platform for cultural heritage data with advanced faceting features. In addition, the study touches on the topic of preserving data by emphasising the necessity of sustainable technological solutions, while software rapidly advances.

Additionally, the study explores the potential of AI-generated metadata to bridge gaps between platforms and enhance interoperability, while acknowledging the need for clear labelling and potential limitations of such approaches. The study also touches on the topic of preserving data by emphasising the necessity of sustainable technological solutions, while software rapidly advances.

5.1 How to access files via Internet

One of the most basic skills that we should have in today's digital world is accessing files from the internet. Downloading documents, streaming media, and sharing photos in this digital jungle can be done with multiple strategies from the unlimited web ecosystem. The most common way is to use a web browser to open files directly using URLs or download them onto your device. For more advanced needs, you could resort to file transfer protocols like FTP, cloud storage services, or even command-line tools. Every one of these approaches has its relative strengths for use in various situations, from browsing casually to professional file management. It can be very helpful to have an idea about these alternatives and it will help one find their way around and make the most out of what the web offers.

- Web browsers: Directly accessing files through URLs.
- File Transfer Protocol (FTP): For transferring files between computers on a network.
- HTTP/HTTPS protocols: Used by web browsers and other applications for secure file transfers.
- Cloud storage services: Like Dropbox, Google Drive, or OneDrive.
- Torrent clients: For peer-to-peer file sharing.
- Command-line tools: Such as “wget” or “curl” for downloading files.
- APIs: Programmatic access to files hosted on various platforms.
- WebDAV: Protocol for collaborative editing and file management.
- Rsync: For efficient file transfer and synchronisation.
- Email attachments: Sending and receiving files via email.

All of them have their pros and cons mostly because of file size limitations, the number of files that need to be transferred or ease of use.

While Sketchfab offers Direct Download via its interface in a web browser there is no working Plugin to query and download directly to UE5 (02. September 2024). Openheritage3D is used as Data vehicle for CyArk; its rather minimal search functionality hides the often very good data behind a “send by mail” system.

5.2 State of the Art-Overview of CH Platforms with 3D Assets

Examples on this list exemplify the current state of the art regarding 3D repositories and databases.

Name	Link	Access
Sketchfab Cultural Heritage & History 3D models	https://sketchfab.com/categories/cultural-heritage-history	DDL, API-(Viewer, Download, Login, Data)
Europeana	https://www.europeana.eu/en	DDL, API-(Search, Record, Download, Metadata)
Smithsonian 3D Digitization	https://3d.si.edu/	DDL
CyArk	https://www.cyark.org/	Photogrammetry Data is provided on request (selected projects partner with Open heritage)
Open Heritage 3D	https://openheritage3d.org/	Photogrammetry / Lidar Data is provided on request
Metropolitan Museum of Art	https://www.metmuseum.org/art/collection/search?showOnly=openAccess	42 3D data items via Sketchfab
The British Museum	https://sketchfab.com/britishmuseum	269 3D data items via Sketchfab
Wikimedia	https://www.wikimedia.org/	DDL, API
Morphosource	https://www.morphosource.org/	Download Request, API
Virtual Curation Lab	https://vcuarchaeology3d.wordpress.com/	Moved to Sketchfab
Zamani Project	https://www.zamaniproject.org/	On Sketchfab, not downloadable

During our research we have been focusing on 3D-Data of Cultural Heritage assets.

The researched CH-3D Data is mostly accessible for users via Direct Links for single Download of a file through a web browser. Databases hosted by IMPULSE partners are not part of this overview and will be assessed separately.

5.2.1. Sketchfab[43]

Sketchfab is a web service to easily publish and explore online 3D/VR/AR content. The concept for this was given birth initially in France during 2012, from the minds of Alban Denoyel, Cédric Pinson, and Pierre-Antoine Passet, as an answer to the display of 3D models over the web. The platform relies on WebGL technology, so users are able to publish and view such content within their web browser without special software. It accepts many 3D file formats and supports embedding on other websites. Since then, Sketchfab has grown to serve every audience—from 3D artists and designers to developers. Its applications range in many sectors, such as gaming, architecture, and cultural heritage. The website also has a marketplace where users can buy or sell their 3D models. Lately, in 2021, Epic Games, creator of Unreal Engine and Fortnite, announced the acquisition of Sketchfab. That is in line with Epic's broader acquisition strategy in the 3D graphics and gaming industry. Therefore, Sketchfab might disappear after the Launch of fab.com Quote from the website *"Creators offering free or for-purchase products across UE Marketplace, Sketchfab and the ArtStation Marketplace will be able to continue selling on those platforms during Fab's Alpha period. In 2024, UE Marketplace, Quixel, Sketchfab, and ArtStation Marketplace will all roll up into one destination: Fab."*[44] This is another indication that relying on existing platforms / content aggregators may prove to be problematic for IMPULSE, since the probability of support being rescinded in the future cannot be ruled out.

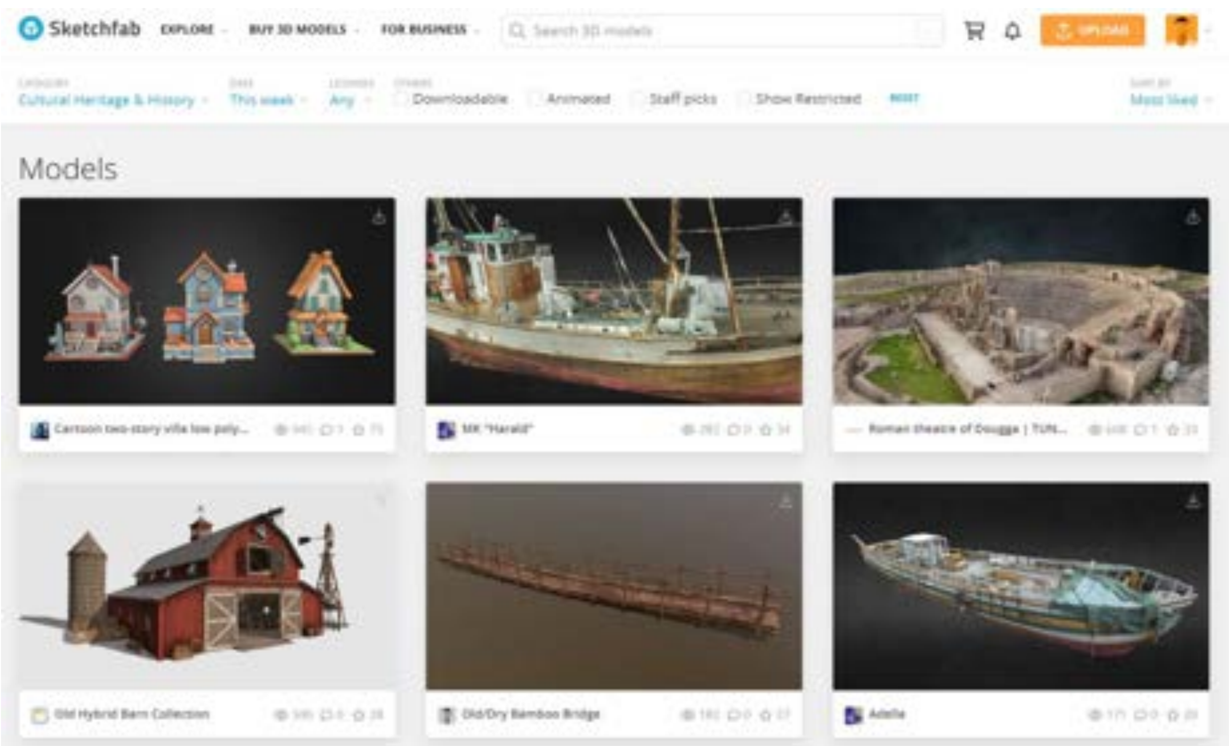

Figure 26. Sketchfab Model Results Page

[43] Sketchfab | https://sketchfab.com/
[44] Fab | https://www.fab.com/

Although Sketchfab offers a wide range of importers[45] for DCC's, these often lack updates. For example, the latest importer for Unreal Engine has been available on Github since 2021 and there is no update for the most commonly used Version of 5.0 and upwards.

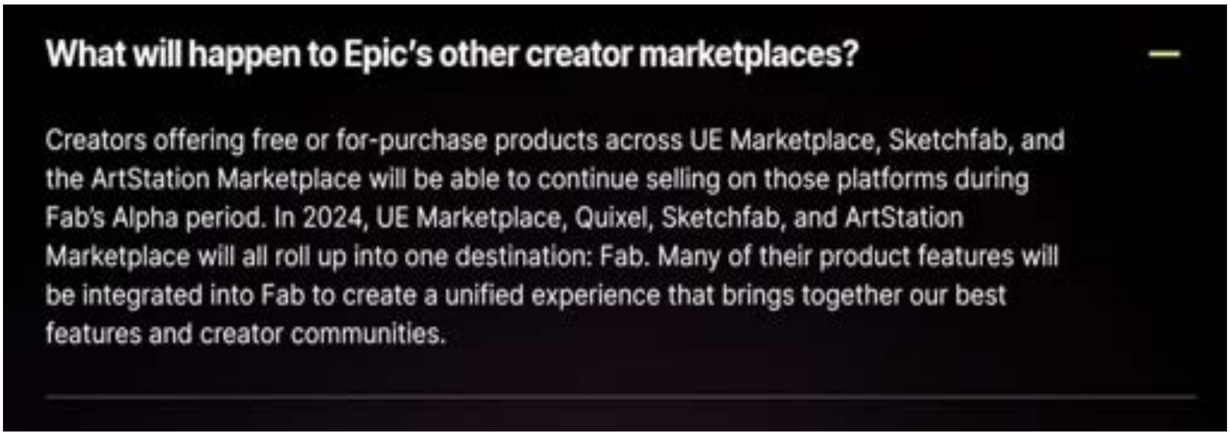

Figure 27. No Result.

Sketchfab's announcement to enable cultural organisations to dedicate their 3D scans and models to the Public Domain through the Creative Commons Public Domain Dedication (CC0) marks a significant advancement in the democratisation of cultural heritage. This initiative paves the way for museums and similar entities to share their 3D data more openly, contributing numerous remarkable 3D models to the public domain, many for the first time. This move significantly enhances the accessibility of ancient and modern artefacts, objects, and scenes for 3D creators worldwide, facilitating their download, reuse, re-imagination, and remixing.

In a collaborative effort with 27 cultural organisations from 13 different countries, Sketchfab proudly welcomed the Smithsonian Institution alongside its open access program, highlighting the initiative's broad appeal and significant impact. The introduction of CC0 at Sketchfab not only expands the repository of freely available 3D models but also simplifies the process for 3D creators to engage with and repurpose cultural and historical data for various creative and commercial projects without the need for attribution.

Since adopting Creative Commons Attribution licences in 2014, Sketchfab has seen over 300,000 3D models shared under these terms, facilitating generous reuse across artistic and academic endeavours. The shift to CC0 dedication for cultural heritage content represents a deeper commitment to fostering artistic and academic reuse of 3D data under clear, accessible terms, allowing for even broader application and innovation.

Sketchfab's implementation of CC0 dedication aligns with the global trend towards open access policies amongst the world's leading cultural institutions. This initiative indeed provides a platform that makes it easier for organisations to align their digital 3D

[45] Sketchfab importers: https://sketchfab.com/importers

collections with open access policies. It has to be stressed though that SketchFab is a commercial initiative and Cultural Institutions pay to publish high resolution models there. It is however, the Cultural Institutions that own the collections, which have embraced the open access movement and are actively supporting this approach by often adopting a CC0 policy, thus enhancing the global accessibility and preservation of cultural heritage in the digital era. SketchFab is merely facilitating this process by providing the context for presenting this CC0 content.

The launch collaborators, including renowned museums, libraries, art galleries, and archaeological projects, exemplify the diverse and rich collections that have embraced this initiative. From ancient artefacts to scientific innovations, the public domain 3D models on Sketchfab offer an unparalleled resource for exploration, education, and creative reinterpretation, providing accessibility to our global cultural heritage. It has to be stressed though that the 3D models that his resource consists of may be of varying quality and resolution.

5.2.2. Europeana[46]

Europeana was launched in 2008 as an initiative of the European Union and born from a vision of making all Europe's cultural and scientific heritage accessible to all across a single multilingual online portal. It was inaugurated with a letter from six European leaders to the President of the European Commission in March 2005, calling for the establishment of a virtual European library. This is a metadata aggregator concerning millions of cultural items kept in the collections of many various European museums, libraries, archives, and audio-visual collections. The items may include books, paintings, films, museum objects, and archival records. However, Europeana does not host the digital objects but gives links to content on the providers' own sites.

Over the years, the service developed from a proof of concept into a full-scale operation. The platform has suffered with the aggregation of metadata coming from various sources, which has been more streamlined with the creation and adoption of the Europeana Data Model. Next to that, it has suffered because of compatibility issues in relation to rapidly changing digital technologies. It has also expanded its service to include APIs for developers and tools for use in education. Today, Europeana remains a centre of digital European cultural heritage for the objectives of research and education, including creative reuse. It is the result of a joint effort to preserve and share their cultural wealth as a whole in the digital age on the part of the EU and its member states. Europeana is part of the consortium and a full partner for the ECCH (European Cloud for Cultural Heritage).

[46] Europeana | https://www.europeana.eu/en

Figure 28. The Europeana Homepage

5.2.3. Smithsonian 3D Digitization[47]

The Smithsonian Institution, a group of museums and research centres administered by the U.S. government, has been working on digitising its collections since the early 2000s. This process involves creating digital versions of physical objects, specimens, and documents held by the institution. The digitization program spans the Smithsonian's 19 museums, 9 research centres, libraries, archives, and the National Zoo. It includes capturing images, 3D scans, and other digital representations of items, along with cataloguing them with metadata. In 2020, the Smithsonian launched its Open Access program[48], releasing millions of digital assets into the public domain. This move allows free use of these materials, though the impact and utility of this access vary depending on user needs and interests.

"The 3D Program is a small group of technologists working within the Smithsonian Institution's Digitization Program Office. We focus on developing solutions to further the Smithsonian's mission of "the increase and diffusion of knowledge" through the use of three-dimensional scanning technology, analysis tools, and our distribution platform." [49]

The Smithsonian 3D Scan Lab acknowledged a necessity for Metadata automation and API access to its collection.

[47] Smithsonian 3D Digitization | https://3d.si.edu/
[48] Smithsonian Open Access program | https://www.si.edu/openaccess
[49] Smithsonian Open Access program | https://3d.si.edu/about#:~:text=The%203D%20Program,our%20distribution%20platform

Additionally, the Smithsonian Institution provides the Smithsonian Voyager, an open-source 3D explorer and authoring tool suite, which affords 3D viewing on the web, quality inspection and authoring of experiences, annotations, articles and tours.

Figure 29. Smithsonian 3D Digitization Homepage


Currently, we are looking for partners to solve the following challenges:

- finding ways to automate and scale parts of our process so that we can transition to a higher-throughput operation, while maintaining scanning quality and the highest level of safety for the objects and specimens being scanned;
- creating an application program interface (API) that allows external platforms to connect to the Smithsonian content and seamlessly present it to their user base;
- developing ways to manage, organize, and share the large amounts of 3D data and metadata (that is, data about the 3D data) that we collect, allowing viewers to understand where the models they are looking at came from and how best to interpret them;
- enabling curators and other subject matter experts to enhance 3D models with annotations, creating stories around those models that enrich their educational content and blend effortlessly with the viewing experience;
- creating an open source, web based 3D viewer that will allow users to appreciate the 3D models and data we create, regardless of what technology platform they use; and
- building an open source community around the development and use of the applications we will create.

Figure 30. Smithsonian About Page - Partnership Advertisement[50]

[50] Smithsonian About Page - Partnership Advertisement | https://3d.si.edu/about#:~:text=Currently%2C%20we%20are,we%20will%20create

5.2.4. CyArk[51]

CyArk was founded in 2003 by Ben Kacyra, an Iraqi-born engineer and entrepreneur. The inspiration for CyArk came after the Taliban's destruction of the Bamiyan Buddhas in Afghanistan in 2001. Kacyra, who had co-invented a portable 3D laser scanning system, recognized the potential of this technology to preserve cultural heritage sites digitally.

The organisation's name, CyArk, is derived from "Cyber Archive," reflecting its mission to create a digital archive of the world's cultural heritage sites. CyArk uses advanced technologies like 3D laser scanning, photogrammetry, and traditional survey techniques to capture detailed 3D models of heritage sites.

Over the years, CyArk has documented hundreds of sites across all six continents. These range from ancient ruins like Pompeii to modern structures like the Sydney Opera House. The data collected is used for conservation, education, and virtual tourism.

The organisation's impact varies. While it has successfully created digital records of many sites, the practical applications and accessibility of this data for conservation, research, and public engagement continue to be areas of development and discussion in the heritage preservation field. In other words, they did a great job capturing the CH-sites but the data is not fully accessible.

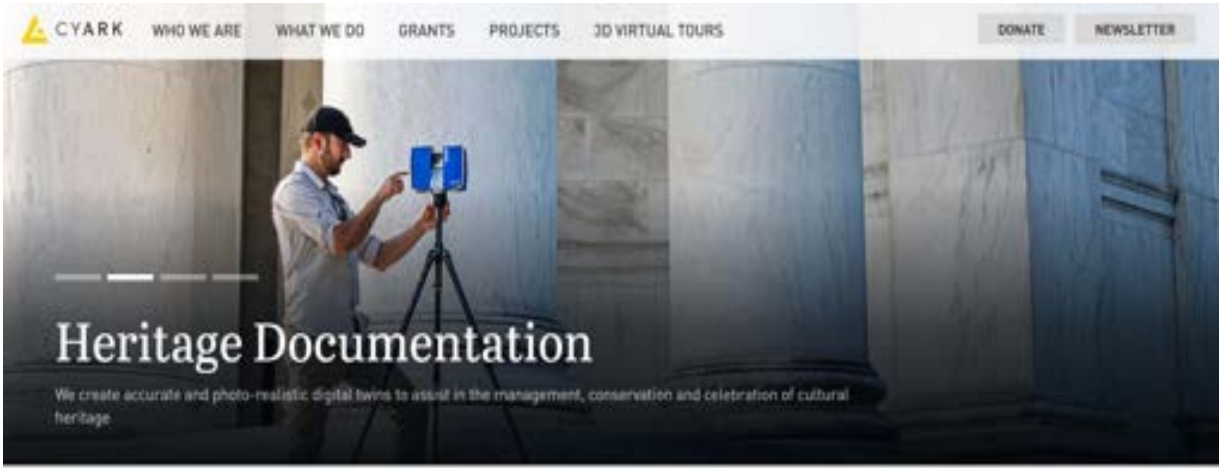

Figure 31. CYARK Homepage

[51] CyArk | https://www.cyark.org/

Figure 32. CYARK Projects Page

5.2.5 Open Heritage 3D

OpenHeritage3D[52] is a collaborative development to advance the application of 3D technologies in documentation and preservation of cultural heritage. OpenHeritage3D started as part of a collaboration between CyArk and the National Center for Preservation Technology and Training (NCPTT), a research arm of the U.S. National Park Service. It was a 2019 project to achieve this through the development of a central repository for 3D data related to cultural heritage sites. The platform hosts an open-access database that enables researchers, cultural heritage professionals, and the general public to access high-quality 3D datasets of heritage sites and monuments from around the globe in 3D documentation formats, among others, including point clouds and mesh models. OpenHeritage3D is designed to address some critical challenges in the field of digital heritage:

- Data availability: By making 3D data freely available, it allows wider use for research and education purposes, as well as in efforts of conservation.
- Standardisation: The project promotes best practices in both data capture and processing methodologies.
- Long-term preservation: It provides a way to store large 3D data sets, which can be difficult for individual institutions.

While the search page doesn't have any necessary filters, for example to search for a date

[52] OpenHeritage3D | https://openheritage3d.org/

published, the point cloud viewer is a bit slow (but rich in features) and it's not always specific why this is cultural heritage, the original data is mostly high quality. Which is also the problem, there are only the source files (lidar or pictures), no final model, no downloadable preview model or textures. Unfortunately, it can only be accessed by email request.

Only if the Openheritage link is displayed there will be a link to access the recording data at the open heritage site.

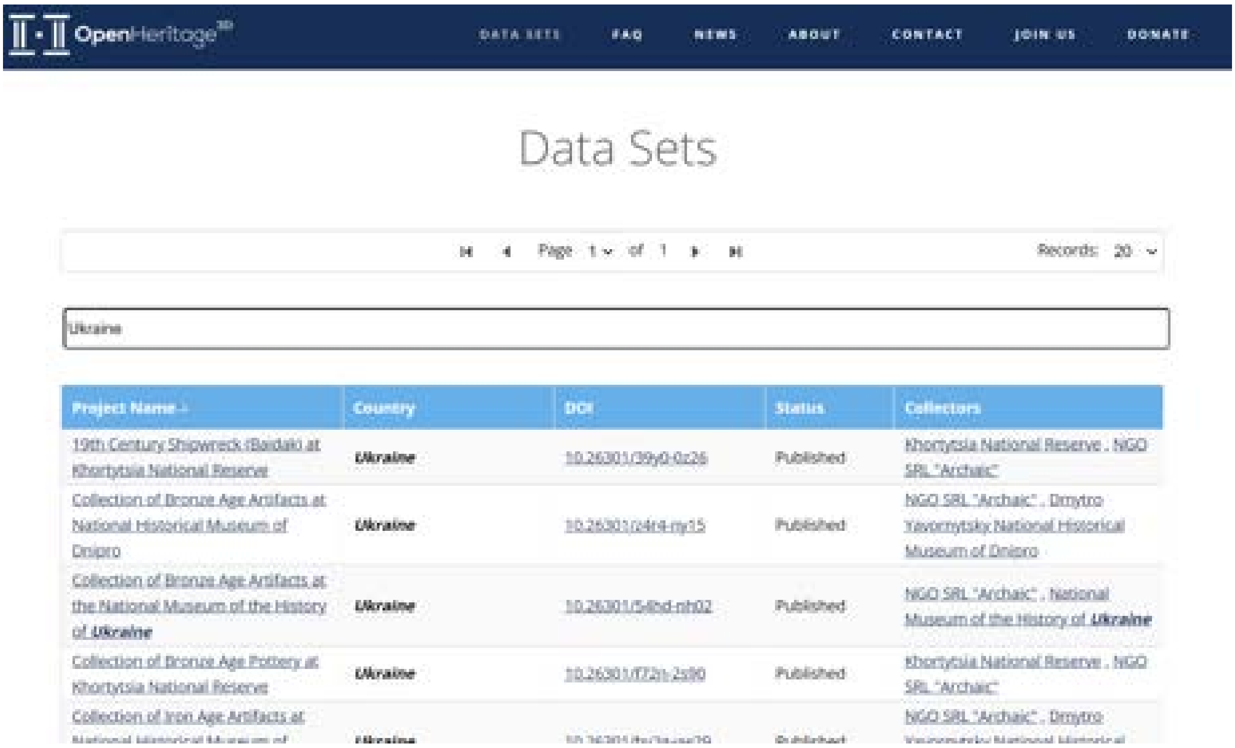

Figure 33. OpenHeritage3D Data Sets Page

5.2.6. Metropolitan Museum of Art

The Metropolitan Museum of Art[53], founded in 1870 in New York City, is one of the most important cultural institutions globally. Holding a collection of more than 2 million works of art from a span of 5,000 years of human creativity, The Met exemplifies the encyclopaedic museum that developed in the late 19th and early 20th centuries. The museum is divided into 17 curatorial departments, each specialising in geography and temporal specifics. Around the onset of the 21st century, the Met initiated discussions on the impact of digital technologies for the collection management objectives of public access and scholarly research, as most other cultural institutions did. Inaugurated in the early 2000s, the museum's digitization program focused on Image capture and metadata creation. The museum has a different approach on 3D models. From their point of view 3D assets are for visitors who want to 3D print at home. The museum encourages visitors to create photogrammetric models of their collection[54]. There is no attempt for professional 3D Scans.

3D Assets by Scan enthusiasts are published on various sites as Sketchfab[55] or Cults3D[56].

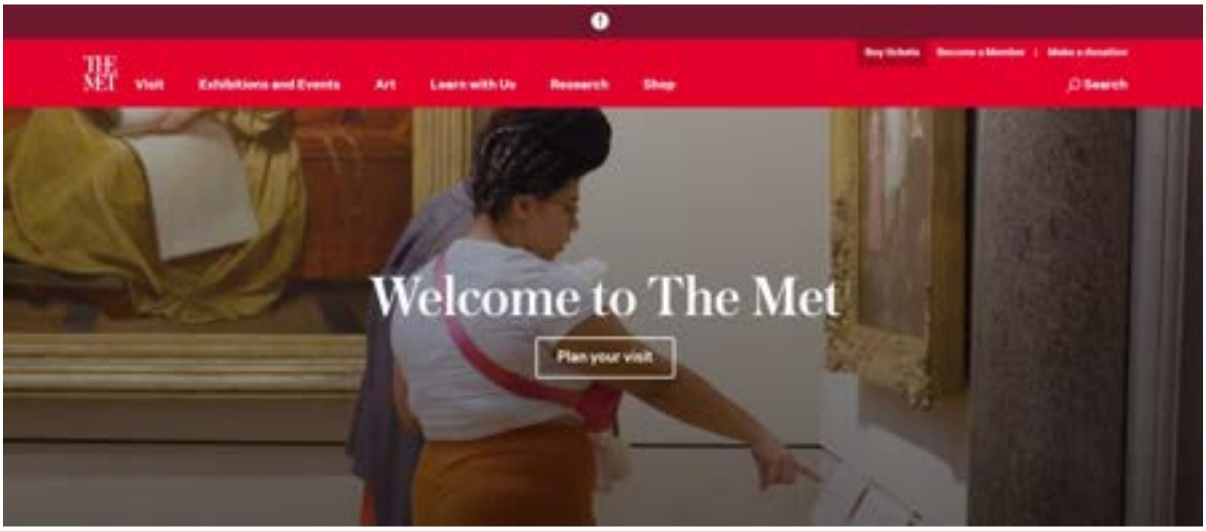

Figure 34. The Metropolitan Museum of Art Homepage.

5.2.7. The British Museum[57]

The British Museum, which was founded in 1753 and located in London, is one

[53] Metropolitan Museum of Art | https://www.metmuseum.org/
[54] Metropolitan Museum of Art 3D assets| https://www.metmuseum.org/articles/3d-printing
[55] 3D assets by Scan on Sketchfab| https://sketchfab.com/tags/metropolitan-museum-of-art
[56] 3D assets by Scan on Cults3D | https://cults3d.com/en/users/metmuseum/3d-models?srsltid=AfmBOop_9QZa-6sAmopnQG7CzZ6asPT8MJXgK9EcLgc7iDirzFR7Xpkv
[57] The British Museum | https://sketchfab.com/britishmuseum

of the world's most renowned institutions for understanding human history, art, and culture. Through a collection of about 8 million works originating from all continents, it is a major world heritage base. The colonial history of Britain remains an important aspect in the origin and development of this museum, which still influences its collections, research orientation, and public engagement today.

The British museum announced in 2023 to scan / 3D scan their entire collection, creating and updating 2.1 million datasets[58]. Which might be a result of the legal action taken by the IDA (Institute for Digital Archaeology) for refusal to scan the Elgin marbles. The initiative also raises legal questions[59].

269 3D models can be found on SketchFab[60] including the rosetta stone and the Granite head of Amenemhat III, the resolution varies vastly, while a 54 MB file for the Rosetta stone might be sufficient, the 10 years old 6MB file for the latter is surely not. Unfortunately, there is no link to the source files.

The British Museum is at the time of this writing still fundraising for a Photogrammetry Rig to do 3D scans.

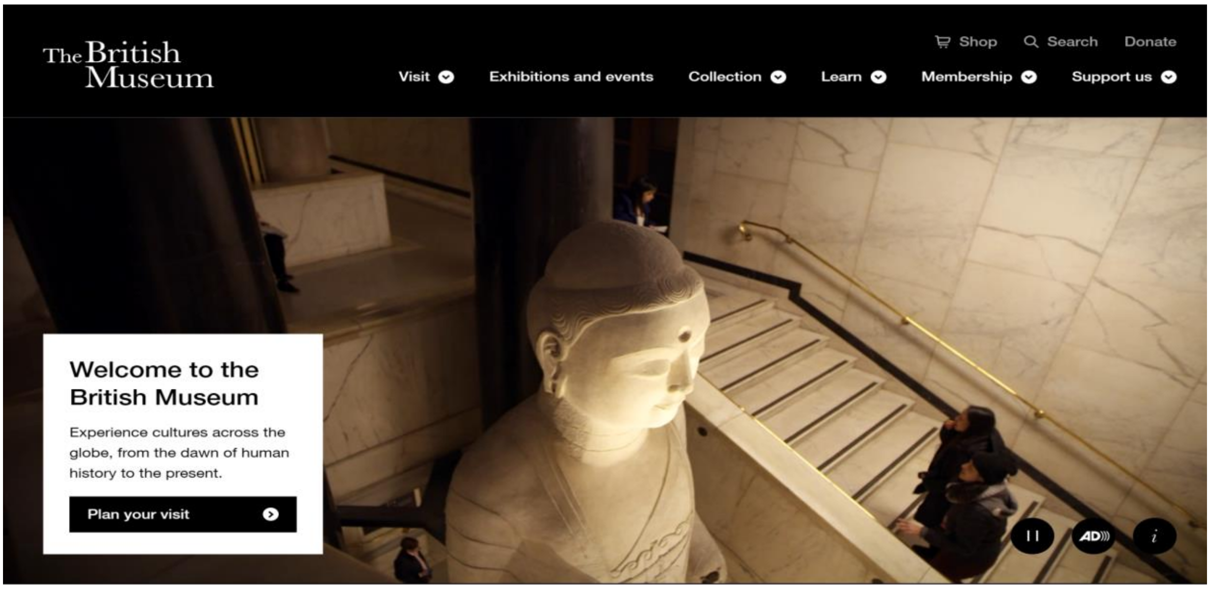

Figure 35. The British Museum Homepage

58 The British Museum datasets | https://www.britishmuseum.org/sites/default/files/2023-10/British_Museum_sets_out_plans_to_digitise_fully_the_collection.pdf
59 Legal questions on the British Museum datasets | https://www.ip-brief.com/blogs/is-the-british-museum-losing-its-marbles
60 The British Museum 3D models on Sketchfab | https://sketchfab.com/britishmuseum

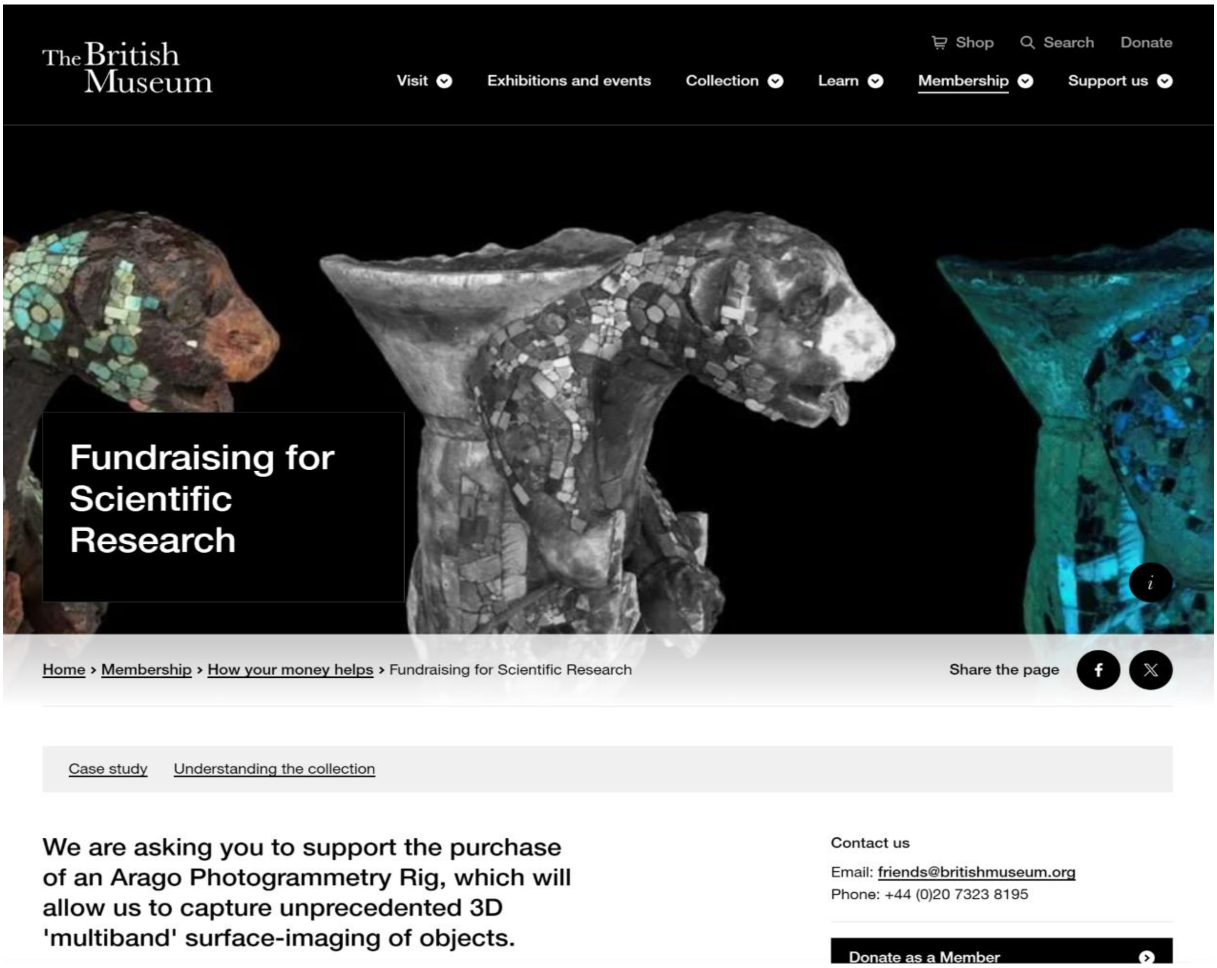

Figure 36. The British Museum Membership Page[61]

5.2.8. Wikimedia[62]

The Wikimedia Foundation, the nonprofit that operates Wikipedia and the other open projects, is extending its mission to include 3D digital assets. At the crossroads of open knowledge, cultural heritage and emerging technologies.

Wikimedia began to make it possible to use files on Wikimedia Commons in 2012, and basically provided most 3D files for Wikipedia pages. That would allow upload and display of 3D models in various formats like STL and OBJ.

There is a guide to create 3D Models for Wikimedia but we didn't find any.[63]

[61] The British Museum Membership Page | https://www.britishmuseum.org/membership/how-your-money-helps/fundraising-scientific-research
[62] Wikimedia | https://www.wikimedia.org/
[63] Guide to create 3D models for Wikimedia | https://en.wikipedia.org/wiki/Wikipedia:Guide_for_creating_3D_models_for_Wikipedia

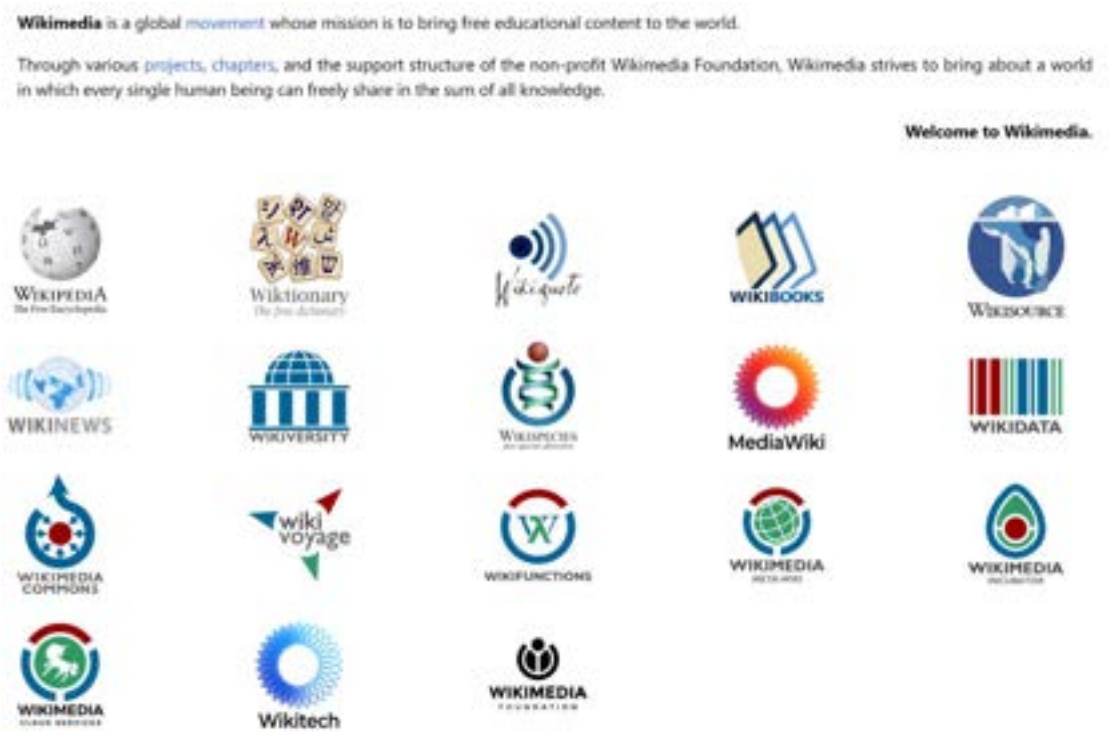

Figure 37. Wikimedia Homepage

5.2.9. Morphosource[64]

Morphosource is an example of a well organised repository in a fixed scientific field.

It is a web-based repository and database designed to store, share, and analyse 3D digital data related to biological specimens. It was first launched in 2013 at Duke University and became one of the most significant developments in digital morphology and biodiversity informatics. Here is a scientific intro to MorphoSource: To serve this need for a centralised place for managing and sharing 3D data in biological research, and especially disciplines like comparative morphology, palaeontology, and evolutionary biology, the development of MorphoSource was initiated. The platform supports all these types of 3D data either from CT scanning, surface meshes, or photogrammetry models.

64 Morphosource | https://www.morphosource.org/

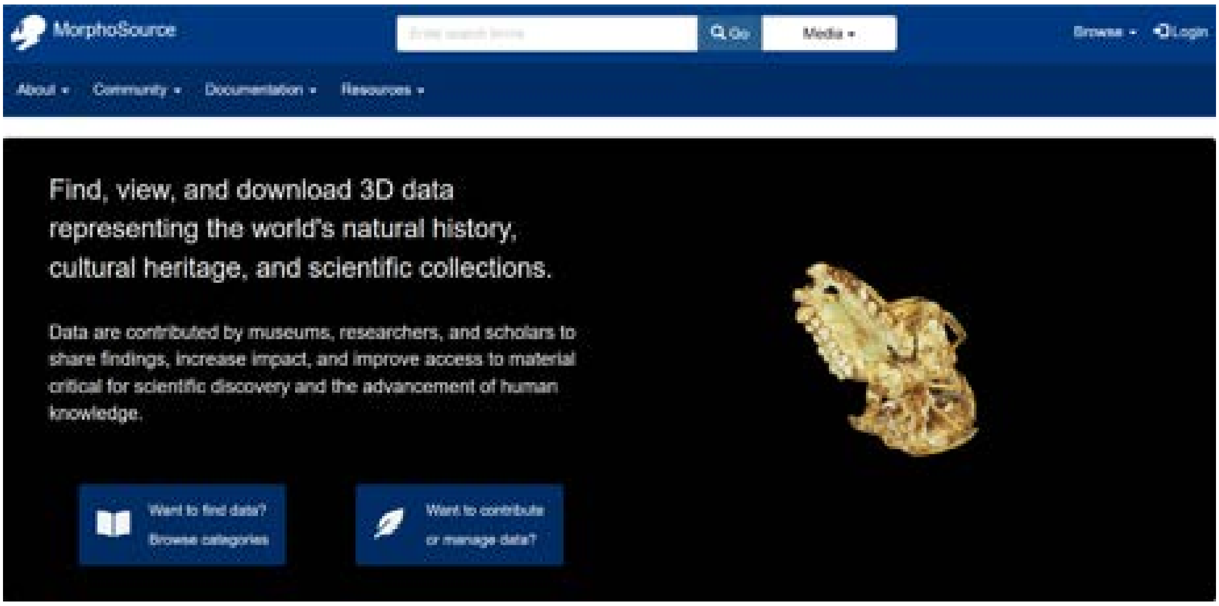

Figure 38. MorphoSource Homepage

5.2.10. Virtual Curation Lab

We included the Virtual Curation Lab (VCL)[65] as an example of the importance of risk assessment / discontinued projects / projects no longer in active development (see also AthenaPlus etc) - it needs to be highlighted that online repositories need to take long-term sustainability of software platforms into account. VCL can't be reached on the website, they moved all their assets uncurated to SketchFab which is a collection of 3862 models ranging from gravestones, tombs to shark teeth. In addition, not even the company that built the 3d Scanner still exists.

[65] Virtual Curation Lab| https://vcuarchaeology3d.wordpress.com/

5.2.11. Zamani Project and Sudan Memory

The Zamani Project[66], formally known as the Zamani Project for African Cultural Heritage Sites and Landscapes, is a significant initiative in the field of digital heritage documentation and preservation. Established in 2004 at the University of Cape Town, South Africa, the project focuses on creating high-resolution digital records of African cultural heritage sites. The website of the Zamani Project provides links to sketchfab 3D although not downloadable.[67] One can access and download high quality 3D files there.

The Sudan Memory Project[68] is a significant digital humanities initiative focused on preserving and providing access to Sudan's diverse cultural heritage. This project represents an intersection of archival science, digital preservation, and cultural studies. But no 3D files yet and many sights in Sudan deserve to be digitally preserved through its natural decline by the sahara.

5.2.12. Other relevant initiatives

Scan the world (STW) is not included although it has a large user base and the collection is still there, while the asset browser only gives 404 sites. It is not included in the list above because it is uncurated, does not belong to an institution (but institutions like the Danish Statens Museum for Kunst provided 382 models), some files are 3D scanned, some modelled for tabletop games. The collection is big (372370 files) with some thousands of them belonging to STW.

A big part of 3D scanning is the recreation of the 3D Models by 3D printing or as has been stated at MyMiniFactory[69] to MetaReVerse the files. Which might be why the ScanTheWorld initiative is dead but the files are still there for printing.

Many websites that focused on free / CC0 licence are discontinued as this list shows:[70]

Additional Site

The Memory of the Netherlands[71] includes no 3D assets, it has a great collection, with insufficient search options.

At the following table, there can be found additional findings by research:

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[66] Zamani Project | https://www.zamaniproject.org/
[67] Zamani Project links to Sketchfab | Via >Archive>zivahub.uct.ac.za/zamani_project
[68] Sudan Memory | https://www.sudanmemory.org/
[69] Scan the World, MyMiniFactory | https://www.myminifactory.com/scantheworld/full-collection
[70] Discontinued free/CC0 license 3D model platforms | https://www.reprap.org/wiki/Printable_part_sources
[71] Memory of the Netherlands| https://geheugen.delpher.nl/en

Name	API Documentation	Content	Aggregator / Single Prov	Formats	searchable	Monetised	Copyright	Update frequency
Sketchfab Cultural Heritage & History 3D models	https://sketchfab.com/developers	High	Aggregator	OBJ, FBX, BLEND, 3DS and STL and more	x	yes / no (Depending on Uploader and Plan)	yes / no (Depending on Uploader and Plan)	very high frequency
Europeana	https://europeana.atlassian.net/wiki/spaces/EF/pages/2461270026/API+Suite	High	Aggregator	glTF, X3D, STL, OBJ, DAE, PLY, WRetc	x	no	yes / no (Depending on Uploader)	high frequency
Smithsonian 3D Digitization		3590 objects	Single	Output: obj, glb, gltf, usbz, MD	x	no	CC0 / Usage Conditions Apply	low
CyArk		40 Sites	Single		x	no	depends on Project	low
Open Heritage 3D		460 Datasets	Single	Output: jpg, raw, e57	x	no	Attribution	low
Metropolitan Museum of Art	https://metmuseum.github.io/	??	Single		x	no	Extensive CC0 collection	nA
The British Museum		269 3D data items	Single		x	no	Attribution	nA
Wikimedia	https://api.wikimedia.org/wiki/Main_Page	??	Aggregator	no 3D	x	no		very high frequency
Morphosource	https://morphosource.stoplight.io/docs/morphosource-api/rm6bqdolcidct-morpho-source-rest-api	??	Aggregator	a lot	x	no	yes / no (Depending on Uploader)	nA
Virtual Curation Lab	https://sketchfab.com/virtualcurationlab	3800 data items	Single		x			

5.3. Chapter summary

Challenges of 3D Cultural Heritage Assets

The digital revolution has transformed cultural heritage preservation, with 3D scanning and modelling technologies enabling unprecedented access to collections. However, as we explore the landscape of 3D asset repositories, we encounter significant challenges that hinder the seamless discovery and utilisation of these digital resources.

Fragmentation and Standardization

The digital landscape is highly fragmented, with platforms like Sketchfab, Europeana, and OpenHeritage3D operating independently, apart for the wide variety of institutional repositories. This decentralisation, while fostering innovation, creates a complex journey for users seeking comprehensive access to 3D cultural assets. Moreover, the lack of standardisation in metadata formats, file types, and quality standards across platforms makes it difficult to compare assets or integrate them into unified research projects. Many smaller-scale case studies within research frameworks have been developed. However, there is a significant gap between developing case studies and integrating standardized 3D digitization workflows (data creation, data publication, and data preservation) into the daily operations of heritage institutions. Initiatives such as the Smithsonian 3D Digitization Program or the British Museum’s efforts to scan their entire collections require policy frameworks that not only commit to these goals but also provide the necessary resources to support them. The absence of standards, guidelines, and clearly defined workflows continues to hinder the adoption and implementation of such initiatives.

Accessibility and Quality Issues

While many repositories promote open access, the reality often falls short. Email requests for data access, as required by OpenHeritage3D, create barriers to immediate use. Institutions not always share datasets under Public Domain, CC 0 or CC By mark. In terms of legal frameworks, there can be huge differences in IPR related legislation between countries, even in Europe. Additionally, the quality and consistency of 3D assets vary significantly across and within repositories as technology, software and file formats evolve at fast pace. The British Museum's Sketchfab collection, for instance, showcases wide disparities in file sizes and resolutions among key artefacts. Paradata, information about the processes and methods used in the creation, collection, or transformation of data, offering transparency about how the data was produced or manipulated, is close to non-existent for legacy data sets. Direct Download Links and lack of APIs makes it harder for industry professionals to maintain larger amounts of data.

Technical Challenges and User Experience

Many repositories struggle with the technical aspects of hosting and displaying 3D content. Slow loading times, compatibility issues, and limited viewing options can impede research and frustrate users. These technical hurdles highlight the gap between data capture and creating structured, usable resources for research and education.

Preservation and Long-term Accessibility

As we digitise cultural heritage, we face new challenges in preserving the digital assets themselves. The rapid evolution of file formats and viewing technologies raises questions about long-term accessibility. Projects like the Virtual Curation Lab, which relocated its assets after discontinuation, underscore the need for sustainable storage solutions. Commercial initiatives and platforms raise questions about data storage, data preservation, long term sustainability.

Outlook and Recommendations

Addressing these challenges requires greater collaboration between institutions to standardise approaches to metadata and file formats. Investments in user-friendly interfaces and robust search capabilities could dramatically improve discoverability. Furthermore, providing processed, ready-to-use 3D models alongside raw data could enhance the utility of these digital assets for a broader range of users.

In conclusion, while the landscape of 3D cultural heritage assets holds immense potential, significant hurdles remain. Overcoming these challenges is crucial to creating a truly accessible, standardised, and user-friendly ecosystem that can serve researchers, educators, and the public alike, unlocking the full potential of these digital treasures for future generations.

5.4. Investigating APIs afforded by content aggregators

5.4.1 Definition of an API

API stands for Application Programming Interface. In simple terms, an API is a set of rules and protocols that allows different software applications to communicate with each other. Here's what you need to know:

- Function: An API acts as a messenger that takes requests, translates them, and returns responses between different software systems.
- Analogy: Think of an API as a waiter in a restaurant. You (the user) ask the waiter (the API) for something, and the waiter goes to the kitchen (the system) to retrieve it for you.

- Purpose: APIs enable developers to access specific features or data from another application or service without needing to understand all of its internal workings.
- Examples: When you use a weather app on your phone, it's likely using an API to fetch weather data from a service. When you log into a website using your Google account, that's also facilitated by an API.
- In context: For e.g. Europeana or Sketchfab, their APIs allow developers to access and retrieve information about 3D objects and their metadata from their respective databases, enabling integration of this data into other applications or services.

While the "big three" (Sketchfab, Europeana and Wikimedia) offer API access most of the other researched Databases don't.

In the following sections, we provide a comprehensive overview of the key aspects of the APIs offered by Europeana, Sketchfab, and other relevant platforms. It aims to highlight the core functionalities, strengths, and limitations of each API, particularly in the context of working with digital content and 3D assets. A deeper examination will be conducted on the search and model APIs, as these are critical components for discovering, filtering, and accessing the content across these platforms. We explore how each API handles search queries, filtering options, and metadata retrieval, with a specific focus on their applicability to 3D assets and cultural content. By taking a closer look at the search capabilities and the data structure of these APIs, we will assess how well each platform supports advanced content discovery and interaction.

Through a comparative analysis of the APIs, we will identify the key differences and similarities in their design, functionality, and usability. The comparison will focus on aspects such as the richness of the metadata, flexibility of search filters, support for 3D content, and integration options provided by each platform.

Sketchfab

- Purpose: A platform for hosting, sharing, and selling 3D models.
- Key Features: Web-based 3D viewer, VR/AR support, and a marketplace for 3D assets.
- Community: Artists, designers, and developers share and explore 3D content.
- Uses: 3D visualisation in education, gaming, animation, and virtual experiences.

Europeana

- Purpose: A digital platform for accessing European cultural heritage.
- Key Features: Digitised collections from museums, libraries, and archives across Europe.
- Content: Art, literature, music, and historical records available for public access.
- Uses: Education, research, and cultural exploration with open access to many resources.

Wikidata

- Purpose: A free, open knowledge base providing structured data.
- Key Features: Linked open data for use in Wikimedia projects and external applications.
- Data: Interconnected, machine-readable information on a wide range of topics.
- Uses: Supports Wikipedia, data queries, AI, and applications in semantic web projects.

Feature/Platform	Sketchfab	Europeana	Wikidata
Primary Focus	3D model hosting, sharing, and viewing	Access to European cultural heritage	Structured data repository
Content Type	3D models, VR/AR content	Digitised cultural items (art, books, music, archives)	Data on a wide range of topics (people, places, concepts)
Community	3D artists, designers, developers	Cultural institutions, educators, researchers	Volunteers, data scientists, researchers
Data Accessibility	Public and paid access to 3D assets	Free access, open licences for many items	Open data under Creative Commons CC0 licence
Interactivity	Web-based 3D viewer, VR/AR support	Interactive exhibitions, thematic collections	SPARQL query service for advanced data analysis
Integration	Integrates with 3D software (Blender, Maya)	Integrated collections from over 3,000 cultural institutions	Integration with Wikipedia, AI applications, semantic web
Monetization	Marketplace for buying/selling 3D models	Not focused on monetization, primarily for public access	Not focused on monetization, open data for reuse
Educational Use	Used for teaching 3D design, VR/AR experiences	Used for teaching European history, art, and culture	Used for research, education, data science
Licensing	Mix of open and commercial licences	Mostly open access with some restrictions	All data is open and available under public domain (CC0)

APIs and Developer Tools	API for embedding 3D models	APIs for accessing cultural heritage data	SPARQL query service and APIs for data retrieval
Search and Discovery	Searchable database of 3D models	Search by keyword, thematic browsing, filtering options	Searchable data with query capabilities

Each platform plays a distinct role: Sketchfab focuses on 3D content, Europeana on European cultural heritage, and Wikidata on structured, accessible data for both human and machine use.

Wikidata, as a collaborative knowledge base, offers a vast repository of structured data on a wide range of topics. While it excels in providing rich metadata and interlinking concepts across various domains, its primary focus is not on the hosting or distribution of 3D assets. Unlike Sketchfab, which specialises in 3D models, or Europeana, which provides digitised cultural content with visual representations, Wikidata is more concerned with cataloguing and interlinking information across the web.

Given that our project is primarily focused on 3D content, including the discovery, use, and integration of 3D models, the deeper exploration of Wikidata is beyond the scope of our current research. This is why we will be demonstrating and introducing Sketchfab and Europeana in particular, as they serve as excellent examples of platforms that are well-suited for working with 3D assets and digital cultural content, which aligns closely with our objectives.

5.4.2 API Access

In this section, we will dive into the technical details of accessing and utilising the APIs provided by Europeana, Sketchfab and Wikidata. The goal is to understand how these APIs enable interaction with their vast repositories of digital content, with a particular emphasis on 3D assets and cultural heritage data. We will explore the authentication methods, available endpoints, and the overall structure of the APIs, highlighting how developers can efficiently retrieve and manipulate data. This exploration will set the foundation for deeper comparisons and practical demonstrations of each platform's capabilities and inform the design of the content administration features of the IMPULSE platform.

Platform	API Types	Key Features	Authentication	Use Cases	Documentation
Sketchfab	Viewer API, Data API, Download API	Embedding 3D models, managing accounts, VR/AR support	OAuth2	3D content integration, virtual/augmented reality	Comprehensive docs, community support
Europeana	Search API, Entity API, Annotations API	Access to cultural heritage data, contextual info	API key	Cultural heritage exploration, educational apps	Detailed docs, developer portal
Wikidata	SPARQL Query API, REST API, MediaWiki Action API	Querying structured data, editing and retrieving items	OAuth, API tokens	Knowledge graphs, AI, semantic web projects	Extensive docs, tutorials, query editor

Sketchfab APIs

Viewer API

This allows the user to embed and control Sketchfab's 3D viewer on your website or application. It is possible to manipulate models, control cameras, interact with the scene, and even integrate with VR/AR.

In the context of our project, while the Sketchfab Viewer API is a nice feature, it is not a crucial component for our needs. Although it provides useful functionality for embedding and interacting with 3D models, it does not play a significant role in the core objectives we are focusing on.

Sketchfab Data API Overview

The Sketchfab Data API provides access to the platform's extensive collection of 3D models, allowing users to manage assets, retrieve metadata, and search through digital content. The API supports functionality such as uploading, updating, and organising models, as well as querying for specific content based on tags, categories, and licences. It enables integration of 3D assets into applications and automation of workflows.

Key capabilities of the API include:

- Model Search: Query the Sketchfab database for models using keywords, tags, or categories.
- Model Details: Retrieve detailed metadata about specific models, including creator information, tags, and licensing.
- User Data Access: Obtain information about users and their uploaded models.

The API offers a wide range of endpoints for interacting with various platform resources, including:

- Models
- Users
- Me (authenticated user details)
- Collections
- Avatars
- Categories
- Skills
- Environments
- Tags
- Relationships
- Backgrounds
- Matcaps
- Thumbnails
- Likes
- Search
- Comments
- Licences
- Purchases
- Organisations (Orgs)
- Projects

These endpoints provide developers with extensive possibilities for integrating Sketchfab's 3D content into their applications. The following sections will focus on the Search and Models endpoints, with detailed examples of their usage.[72]

Sketchfab Search API Overview

The Sketchfab Search API provides endpoints to efficiently search across different resource types, including models, collections, users, and organisational projects. These

[72] A documentation with all endpoints and models: https://docs.sketchfab.com/data-api/v3/index.html

endpoints enable developers to access and filter Sketchfab's extensive content effectively.

Available Search Endpoints

1. Search Collections
   - Endpoint: GET /v3/search?type=collections
   - Description: Search for collections, which are curated groups of 3D models organised around specific themes or topics.
2. Search Models
   - Endpoint: GET /v3/search?type=models
   - Description: Search for 3D models, with the ability to refine results using filters such as keywords, tags, and categories.
3. General Search
   - Endpoint: GET /v3/search
   - Description: Perform a general search across multiple resource types, including models, collections, and users.
4. Search Organisational Projects
   - Endpoint: GET /v3/orgs/{orgUid}/search?type=projects
   - Description: Search for projects within an organisation, which group and manage multiple models under specific initiatives.
5. Search Organisational Models
   - Endpoint: GET /v3/orgs/{orgUid}/search?type=models
   - Description: Search for models associated with a specific organisation, useful for enterprise-related content.
6. Search Users
   - Endpoint: GET /v3/search?type=users
   - Description: Search for users on the Sketchfab platform, including creators and contributors.

Performing a Search Query Using Postman

To demonstrate the usage of the Sketchfab Data API, let's perform a search query using Postman[73], an API development and testing software.

In this example, we will search for the keyword "apple" to retrieve relevant 3D models from Sketchfab.

Let’s make a GET request with the URL:

https://api.sketchfab.com/v3/search?q=apple

[73] Postman | https://www.postman.com

The response from the API will be displayed in JSON format, containing details about the models that match the search query. Here, we get 3420 lines of JSON.

Figure 39. Response from the Sketchfab Data in JSON format.

When a request gives many results, results are paginated using cursors. Each response will contain these fields you can use to make subsequent requests:

- **next**: full URL containing the next results.
- **previous**: full URL containing the previous results.
- **cursors**: an object containing the previous and next cursor that you can use to build the URL to the previous/next results.

By default, pages contain 24 items. You can use the count parameter to change the number of items per page. This parameter is capped to 24: it will be ignored if a higher value is passed; the default value will be applied instead.

Models Endpoint Overview

The models endpoint of the Sketchfab Data API provides detailed information about a specific 3D model using its unique identifier (uid).

Endpoint

URL: GET /v3/models/{uid}

Key Response Fields:

- uid: Unique identifier of the model;
- name: Name of the model;
- description: Brief description of the model;
- publishedAt: Publication date and time;
- updatedAt: Last update date and time;
- createdAt: Creation date and time;
- viewCount: Total views;
- likeCount: Total likes;
- commentCount: Total comments;
- animationCount: Number of animations;
- materialCount: Number of materials;
- textureCount: Number of textures;
- vertexCount: Number of vertices;
- faceCount: Number of faces;
- soundCount: Number of sounds;
- isDownloadable: Whether the model is downloadable;
- isAgeRestricted: Age restriction status;
- isProtected: Protection status;
- price: Model price, if applicable;
- pbrType: PBR type used;
- source: Source information;
- embedUrl: URL for embedding the model;
- viewerUrl: URL to view the model;
- editorUrl: URL to edit the model;
- tags: Tags associated with the model;
- categories: Categories related to the model;
- thumbnails: Thumbnail images;
- licence: Licence information;
- user: Information about the uploader.

Retrieving Model Details Using the Model Query

After performing a search query, you can further explore the details of a specific model by using the GET /v3/models/{uid} endpoint. In this example, we'll retrieve detailed information about the model with the uid "28f9db4c2b4849a29f0ea17b9e6dd856", which was one of the results from our search query for "apple."

Performing also a GET request with the following URL:

https://api.sketchfab.com/v3/models/28f9db4c2b4849a29f0ea17b9e6dd856

returns 349 lines of JSON with all the details and information about that specific model.

Figure 40. Response from the API in JSON format.

Download API

The Download API is an extension of the Data API. It's a REST-like API that allows developers to download 3D models from Sketchfab.

See "archives" field in the search endpoint above.

Downloading models typically requires user authentication with a Sketchfab account. Therefore, end-users would generally need to log in or create a Sketchfab account within the application.

Alternative options that do not require end-user authentication may be available but would need to be discussed with Sketchfab.

Europeana API

The Europeana API enables developers to access the extensive collections of digital content hosted on the Europeana platform and integrate them into their own applications or digital projects. From a technical standpoint, the Europeana API follows RESTful architecture principles. There are various ways to use the API, including the console. However, there are also several libraries for different programming languages, such as Python, Java or NodeJS.

Europeana offers unlimited, free access to its APIs for reading information, with no throttling or usage limits, but requests users to be considerate by adding brief pauses between multiple API calls to manage server load.

Although the API is free to use, it requires an API key for access, which can be obtained by registering on their developer portal.

Comprehensive documentation is provided on the Europeana website[74], which includes detailed guidance on how to query and interact with the data, code examples and best practices for integration. It also offers detailed description of the available endpoints and parameters.

[74] Europeana API Documentation | https://europeana.atlassian.net/wiki/spaces/EF/pages/2385313793/Europeana+APIs+Documentation

API Overview

Type of resource	search	retrieval	display	recommendation	contribute	harvest / download
Record *Information about a cultural heritage object*	✅Search API ✅SPARQL	✅Record API	✅IIIF APIs	✅Recommend API	❌	✅OAI-PMH ✅Downloads
Entity *Information about contextual resources that are related to the cultural heritage object*	✅Entity API ✅SPARQL	✅Entity API	❌		✅Entity API	❌
User Set (ie. Gallery) *Information about galleries created by end-users*	✅User Set API	✅User Set API	❌		✅User Set API	❌
Text Content *Digitized text extracted from images or a/v resources*	✅Fulltext API ✅Fulltext Search API	✅Fulltext API	✅IIIF APIs	❌	✅Fulltext API	✅Downloads (partially)
Annotation *Complementary information about cultural heritage objects*	✅Annotation API	✅Annotation API	❌	❌	✅Annotation API	❌

Figure 41. API Overview[75]

EDM

The Europeana Data Model (EDM) is a framework for structuring and representing metadata about cultural heritage objects in the Europeana digital library. EDM is based on Semantic Web technologies, utilising RDF (Resource Description Framework), which is a standard model for data interchange on the Web that allows for the representation of information as subject-predicate-object triples, forming a graph of interconnected data. This use of RDF enables EDM to create a network of linked data that can be easily shared and reused across different systems. By using EDM, Europeana enables better

[75] Europeana API Overview |
https://europeana.atlassian.net/wiki/spaces/EF/pages/2461270026/API+Suite

interoperability between diverse collections and facilitates more sophisticated search and discovery capabilities.

API's

Search API

The API allows programmatically searching the Europeana database with a specific query and responds to all the items that match that query. It supports advanced search capabilities and returns results in JSON format, including metadata like title, description, or media links.

The search API offers similar functionality to the website search, which is shown in Fig. 42[76].

Request:
Endpoint: https://api.europeana.eu/record/v2/search.json

There are two required parameters: "q=" for the query and "wskey=" for the API key.

Example: Search for "stone bowl" with the refinement parameter "qf=" to only include 3D objects:

https://api.europeana.eu/record/v2/search.json?wskey=YOUR_API_KEY&query= stone bowl&qf=TYPE:3D

Further API Request Parameter can be found here:
https://europeana.atlassian.net/wiki/spaces/EF/pages/2385739812/Search+API+Documentation#Request

Response:

The API responds with a JSON object containing metadata about the search results and a list of matching items. This response includes general information such as the total number of results, the current page of results, and for each item, a subset of metadata fields like title, description, thumbnail URL, and links to the full record on Europeana. Further results fields are provided in the documentation

https://europeana.atlassian.net/wiki/spaces/EF/pages/2385739812/Search+API+Documentation#Result-Fields

[76] Europeana Search API documentation | https://europeana.atlassian.net/wiki/spaces/EF/pages/2385739812/Search+API+Documentation#Getting-Started

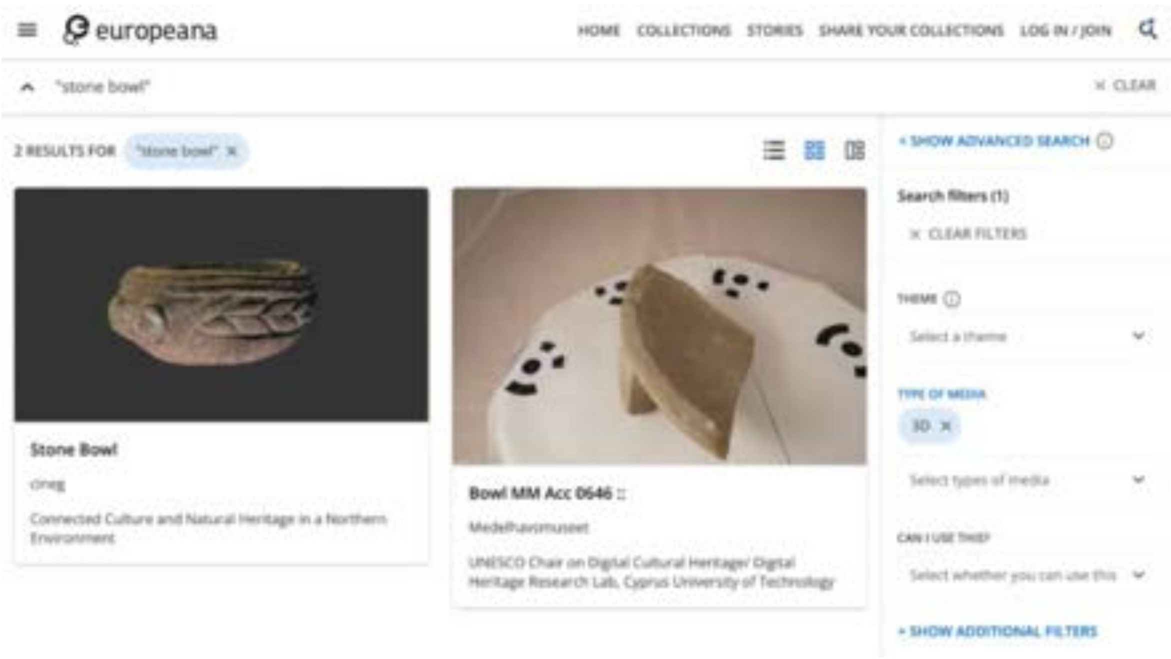

Figure 42. Response of the search query "stone bowl" and the media-type filter set to "3D" on the website of Europeana[77]

Record API:

Used to retrieve detailed information about specific items in the Europeana collection. It provides all data and metadata for a single Cultural Heritage object using a unique Europeana ID, which consists of a dataset ID and a record ID. Both are extractable from the object's URL on the Europeana website, e.g. https://www.europeana.eu/de/item/181/share3d_998 has the dataset ID 181, and the record ID share3d_998 (see Image (2)).

Request:

Endpoint: https://api.europeana.eu/record/v2/[EUROPEANA_ID].[FORMAT]

The EUROPEANA ID is typically in the format of "/DATASET_ID/RECORD_ID", and the file extensions FORMAT is one of the following output formats: .json (default), .jsonld, or .rdf.

Example: Stone Bowl with the DATASET_ID= 181 and RECORD_ID= share3d_998

https://api.europeana.eu/record/v2/181/share3d_998.json?wskey=APIKEY

[77] Response of the search query "stone bowl" and the media-type filter set to "3D" on the website of Europeana | (https://www.europeana.eu/en/search?page=1&qf=TYPE%3A%223D%22&query=%22stone%20bowl%22&view=grid)

Response:

The Europeana Record API returns comprehensive metadata about a specific cultural heritage object representing the EDM metadata record. It includes its unique identifier, basic details (such as title, or date), descriptive information, rights status, provider information, and links to digital representations.

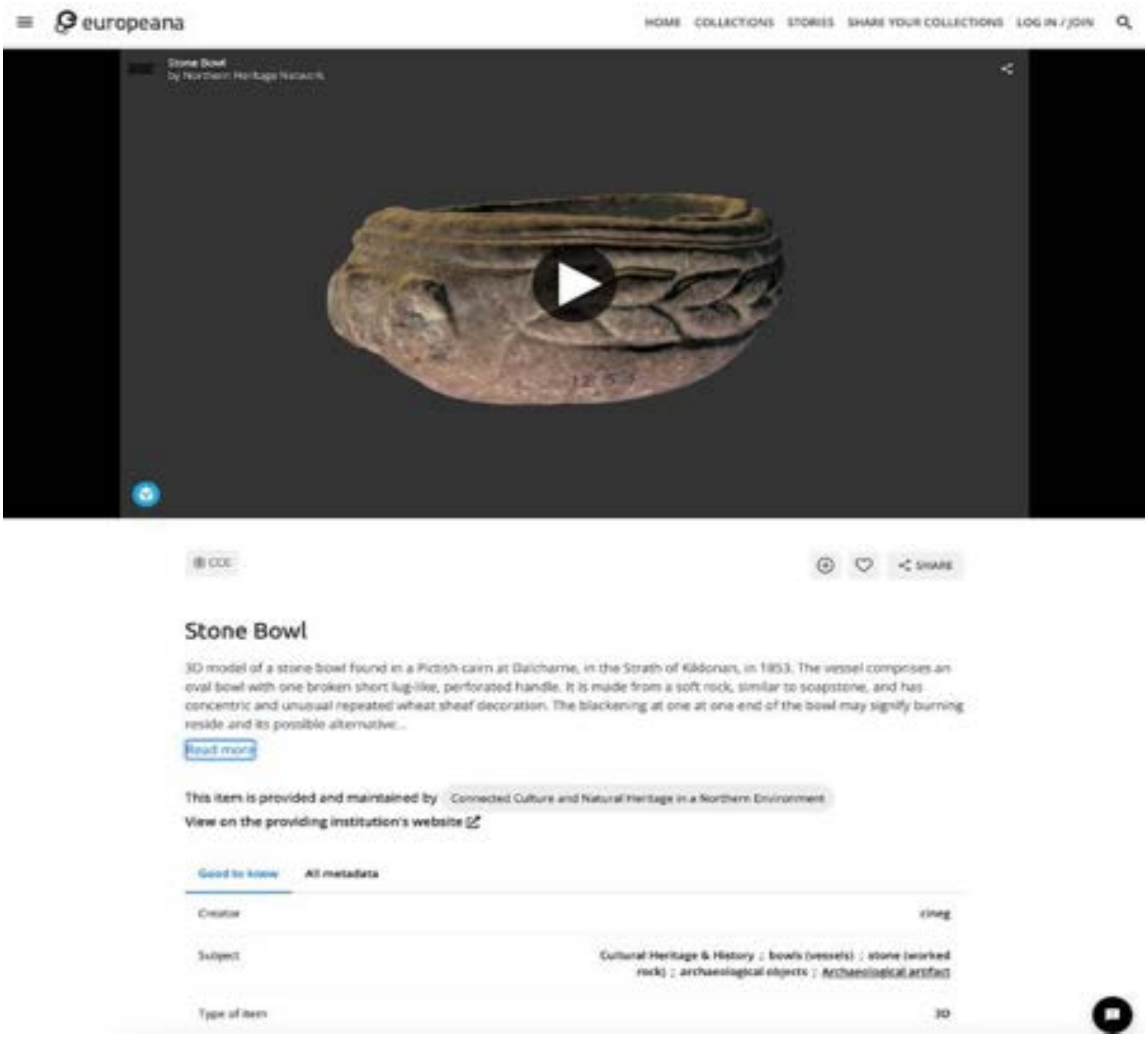

Figure 43. Example of a Cultural Heritage item "Stone Bowl" on the website of Europeana[78]

Entity API: Offers access to contextual information about entities such as people, places, concepts, and time periods related to items in the Europeana collection.

[78] Example of a Cultural Heritage item "Stone Bowl" on the website of Europeana | https://www.europeana.eu/en/item/181/share3d_998

Annotations API: Allows creation, retrieval, and management of annotations associated with Europeana resources, enabling users to add additional context or information to items.

IIIF API: Provides access to high-quality images using the International Image Interoperability Framework (IIIF) standard, allowing for advanced image manipulation and presentation.

User Set API: The User Set API from Europeana enables users to manage and interact with their personalised collections of digital items. It allows users to create, update, and delete sets of items from Europeana's vast cultural heritage collections. Users can organise items into sets, retrieve information about their collections, and adjust the contents as needed.

5.4.3. API Comparison Europeana vs. Sketchfab

The following table provides a side-by-side comparison of the key search parameters and filters available in the Europeana, Sketchfab, and Wikidata APIs. By examining these features, we can better understand how each platform supports content discovery and management, with a particular focus on 3D assets and digital cultural content. This comparison highlights the strengths and limitations of each API, helping to determine which platform is most suitable for specific use cases.

Feature/Filter	Europeana API	Sketchfab API
Main Search	query for text search in metadata fields	q for text search in titles, descriptions, tags
Media Type Filter	type (e.g., IMAGE, TEXT, VIDEO, etc.)	category and tags (e.g., architecture, nature)
Licence Filter	reusability (e.g., Open, Restricted)	licence (e.g., Creative Commons, Public Domain)
Geospatial Filter	place for filtering by location	No direct geospatial filter
Downloadable Filter	Not available	downloadable filter for downloadable models

Animated Filter	Not available	animated filter for animated models
Faceting	Facets by year, provider, country, type	No faceting options
Sorting	By timestamp_created, score, etc.	By likes_count, view_count, published_at
Pagination	rows and start	per_page and cursor for pagination
Embedding	Not focused on embedding	embed option for 3D model embedding
Complexity Filter	Not available	min_face_count / max_face_count for model complexity
Advanced Filters	None	staffpicked, store_item for curated and store items

5.4.4. Metadata Comparison

The following table provides a comparison of some of the technical metadata fields[79] available through the Europeana and Sketchfab APIs. This side-by-side comparison highlights the strengths and focus areas of each platform.

Metadata Field	Europeana API	Sketchfab API
Title	✓	✓
Description	✓	✓
Creator	✓	✓ (as part of user data)
Providing institution	✓	✗
URL to object	✓	✓
Thumbnail URL	✓	✓

[79] The descriptive metadata doesn't follow any standard such as Dublin Core.

Views count	✗	✓
Animation count	✗	✓
Face count	✗	✓
Vertex count	✗	✓
File size	✗	✓
File format	✓	✓
Language	✓	✗
Cultural context	✓	✗
Geolocation	✓	✗
Time period	✓	✗
Related items	✓	✗
Comments	✗	✓

Sketchfab is a platform specifically designed for publishing, sharing, and discovering 3D content. Its API provides detailed technical information about 3D models and focuses on user interaction data. Sketchfab excels in providing:

- Comprehensive 3D model specifications (face count, vertex count, animation details).
- User engagement metrics (views, likes, comments).
- Multiple resolution options for thumbnails and model previews.
- Embed codes for easy integration into websites.
- Categories and tags specific to 3D modelling and design communities.

Europeana provides much more detailed information about the objects themselves, which is a key differentiator from platforms like Sketchfab. This rich, object-specific metadata is crucial for understanding the cultural and historical significance of the items in Europeana's collection.

Here are some key points about Europeana's object-specific metadata:

- **Cultural Context**: Europeana provides detailed information about the cultural background of objects, which is often not available on Sketchfab.

- **Historical Information**: There's typically more information about the time period, historical significance, and provenance of objects in Europeana.
- **Physical Characteristics**: Europeana often includes details about materials, techniques used, and physical dimensions of objects.
- **Institutional Information**: As items come from cultural institutions, there's often information about acquisition, conservation status, and exhibition history.
- **Academic Context**: Europeana may provide links to related literature or research about the objects.

This level of detail reflects Europeana's focus on cultural heritage and its partnerships with museums, libraries, and archives. Sketchfab, being more of a general 3D model platform, typically doesn't provide this depth of cultural and historical context.

5.4.5. Potential for AI-Generated Metadata

To bridge the gap between these two platforms, AI could potentially be used to generate missing metadata:

- **For Sketchfab:**
  - AI could analyse visual features of 3D models to infer cultural context, historical period, or potential materials used.
  - Natural Language Processing (NLP) could extract more detailed object information from titles, descriptions, and user comments.
  - Machine Learning models could suggest related cultural or historical items based on visual similarities.
- **For Europeana:**
  - AI could generate technical 3D model specifications (face count, vertex count) by analysing the 3D files.
  - Computer Vision techniques could be used to detect and count potential animations in 3D models.
  - Predictive models could estimate user engagement metrics based on object features and historical data.

While AI-generated metadata could enhance interoperability between these platforms, it's important to note that such data would be probabilistic and may not match the accuracy of curated information. Any AI-generated fields should be clearly labelled as such and potentially include confidence scores.

5.4.6. API Compatibility Conclusion

In conclusion, while each platform offers valuable API capabilities for accessing and managing digital content, Sketchfab and Europeana stand out in their specific support for 3D assets and cultural heritage data, respectively. Through a detailed comparison of their search functionalities, filtering options, and data structures, it's clear that both platforms provide powerful tools for content discovery and interaction, making them highly relevant to our project's focus on 3D content.

While Wikidata offers rich metadata for a wide range of topics, its scope doesn't align as closely with the 3D asset focus of this research. Therefore, Sketchfab and Europeana serve as prime examples of platforms that meet our specific needs.

While both APIs can be utilised together in projects involving cultural content and 3D assets, their integration may require custom development to bridge their different data structures and content types.

6 State-of-the-art of existing software solutions supporting the development of MUVEs

In the broader context of online social virtual environments and given the specific goals and aspirations of the IMPULSE project, a set of common features and functionalities emerges as a basis of minimum requirements that must be fulfilled by any technological solution to be adopted for the development of the project's virtual environments:

Solution architecture

- Support for the deployment/development of a service providing access to a collection of online, multi-user, persistent, 3D virtual environments, with VR-enabled embodiment, social features, account management, content creation facilities and transaction support.
- Development as a distributed platform involving backend services and local user clients.
- Backend services include account management and authentication services as well as virtual world services.
- Users authenticate once with the platform and can then enter different worlds through the client.
- Users can register for the entire platform with email/password and administer their account via the client.

User embodiment, navigation, interaction

- Support for user embodiment through an avatar, avatar appearance is configurable (to a basic extent) by the user via the client.
- Users can walk on terrain, fly or otherwise move freely within the virtual world for self-guided exploration purposes.

- Users can teleport to select, predefined, world-specific locations in the world to visit key points of interest.

Virtual world features, rendering

- Support for basic physics, solid objects, physics.
- World audio background, in-world interaction sound effects.
- World rendering by client is adjustable in terms of quality vs performance.

Social interaction

- Multiple users can coexist within the virtual world.
- Users can communicate verbally and non-verbally, in a geographically local or global scope within the virtual world or directly with other users.
- Each use is uniquely identified by an alias that appears to all users in proximity within the virtual world and in all communication.

Content management and creation

- Copyright and intellectual property rights of all created content showcased within all virtual worlds shall be fully protected.
- Users can be granted a "Creator" role which entails privileges for object creation and management as well as configuration of various parameters of a certain virtual world instance.
- Creators can add, remove and transform objects available through the backend service in the world.
- Creators have ownership of objects they add in the world and can only remove or modify objects they own, so that multiple co-creators can securely co-work within the same virtual world.
- The client includes functionality for adding objects to the creator's palette/DB/other from available sources.
- The platform includes a web-based interface for administering object sources and collections.

Standards and implementation

- Multi-user functionality is implemented in such a way so that no third-party services are required.
- All implementations are based on well-defined architecture leveraging standard, preferred and documented patterns and practices.
- Client is VR-enabled.
- VR support by client based on established standards, not vendor-specific implementations.
- Exhibit transactions backed by NFT technology and mechanisms.

- Blockchain-secured exhibit transaction history.
- Platform maintains only basic user information required for unique identification, world access and transactions.
- Service databases reflecting, among other things, state of the world, backed up automatically and regularly.
- Specific range of media file formats supported for compatibility with the platform.

Technological solutions currently available for the development of multi-user virtual environments with features and functionalities as listed above can be grouped under two main categories, reflecting respective creative approaches:

1. Online, ready-made platforms available as services offering integrated authoring tools, interaction with objects and exhibits, user-to-user communication and other social facilities, and user authentication and management services.
2. Development platforms, tools and components for in-house application implementation.

Options in the first category focus largely on the creative aspects of a virtual environment creation endeavour and include services such as the following:

- Spatial[80]: A platform that offers tools for the creation of online multi-user virtual reality experiences. Its focus has recently been shifted towards gaming and entertainment but it still offers the Spatial Creator Tools suite for general purpose development. Integration with design and development tools such as Blender and the Unity engine is also offered as well as facilities for importing 3D models and other types of assets. Spatial supports both desktop and immersive access.

- VRChat[81]: VRChat provides extensive world and content creation capabilities using Unity and their VRChat SDK. Its focus is on generic interactive experiences with a strong social element, including online games and social hubs. VRChat supports Meta VR equipment and offers integration with marketplace and diffusion services such as Steam and Google Play.

- Sansar[82]: Advertised as a leading social virtual reality platform, Sansar also supports content creation via integration with the Unity engine. It has a strong focus on sophisticated world-building for social events and online gaming as well as explorable VR experiences in general.

[80] Spatial | www.spatial.io
[81] VRChat | hello.vrchat.com
[82] Sansar | www.sansar.com

- Meta Horizon[83]: A generic virtual world platform for gaming, artistic events or plain social interaction, Horizon by Meta provides in-world content creation capabilities. It has a strong focus on social interaction and, naturally, supports immersion using Meta gear including Quest 2, 3, Pro and Rift S.

- Second Life[84]: Still alive and relevant two decades since its launch, Second Life is a platform that has been extensively used for exhibiting creative and artistic work. Social interaction is a key element of the service and its user base is still large and active. However, it does not seem to keep up with technological advancements as a platform, only offering VR support, for instance, via custom client modifications and not natively.

Other options such as Microsoft Mesh[85] offer content creation, social interaction and immersion functionality among similar lines but are more specifically targeted towards integration with other services such as Microsoft Teams, etc. Options with an artistic orientation such as VR-All-Art[86] and Artsteps[87] seem to be constantly emerging, naturally leveraging both the technological progress in the field and the current hype around VR and the Metaverse; many, though, lack key features or are yet to attract the critical mass of users required to ensure their sustainability.

The second category encompasses a more technical mindset as it requires in-house implementation of virtual environment software in addition to the actual content. This does by no means imply implementation from scratch as, today, numerous development platforms, tools and components are available. Game engines such as Unity and Unreal are prime candidates for a complete, integrated development environment, providing out-of-the-box an extensive range of key capabilities such as:

- Scene and object management.
- Interactivity and user input.
- Diverse user-interface options including desktop, web and XR.
- Powerful and robust object scripting in C# and C++, respectively, in conjunction with comprehensive platform-level SDKs.
- Visual scripting tools that substantially ease development by non-programmers.
- Support for importing multiple asset formats for 3D models, audio, video & files, images, textures, etc.
- Support for audio, physics, networking, sophisticated rendering pipelines, and more.

[83] Meta Horizon | horizon.meta.com
[84] Second Life| secondlife.com
[85] Microsoft Mesh | www.microsoft.com/en-us/microsoft-teams/ microsoft-mesh
[86] VR-All-Art | vrallart.com
[87] Artsteps | www.artsteps.com

Alternative options oriented specifically towards virtual environment development, such as Vircadia[88] and Ethereal Engine[89], are also available, focusing on open-source implementation, collaborative development, etc.

A key characteristic of game engine-based development is that the software has direct, albeit reasonably limited access to the runtime platform, including the filesystem, operating system services and input/output devices, which far exceeds the respective capabilities of ready-made platforms available as online services such as those listed above. This naturally allows for more specialised and cutting-edge use cases involving advanced features such as, for instance, full-body motion capture, sophisticated immersion gear such as treadmills, and exploitation of XR gear SDKs.

In addition to features readily built-into the game engine, numerous supporting components, libraries and services are also available. As an example, Photon[90] and FishNet[91] [can be used instead of Unity's own Netcode for GameObjects (NGO) for networking and multiplayer functionality. Libraries such as NGUI for Unity[92] can substantially ease and empower graphical user-interface design and implementation. SDKs offered by most XR gear manufacturers further enrich the development process with state-of-the-art elements such gaze and hand tracking, environment mapping, etc.

To summarise, the benefits and drawbacks of each option along certain key axes pertaining to the IMPULSE project and the concept of the Metaverse for Cultural Heritage, education and artistic creation in general can be outlined as follows (a green-colour annotation indicates which option has the advantage in each case):

	Third-party services	**Own development**
Free, open-source	✕ Some offer free trials or limited functionality plans	✓ Can be offered as such
Immersive VR	? Not consistently	✓ Can be built as such
Intellectual property safety	? Depends on vendor policy, may be unclear or too	✓ Data hosted internally, any own policy can be enforced

88 Vircadia | vircadia.com
89 Ethereal Engine | www.etherealengine.com
90 Photon | www.photonengine.com
91 FishNet | github.com/FirstGearGames/FishNet
92 NGUI for Unity |assetstore.unity.com/ packages/tools/gui/ngui-next-gen-ui-2413

	restrictive	
Hardware, administration required	✕ None	✓ Substantial
Vendor policies dependent	✓ Subject to restrictions, changes, discontinuation	✕ Service hosted internally, any own policy can be enforced
Data sources/services connectivity	✕ Generally none or very limited	✓ Can be built as needed
Scalability	✕ Generally limited, at a cost	✓ Only depends on internal investment on hardware
Development effort	✕ None or very little	✓ Substantial
Service stability	✓ Guaranteed	? Depends on local factors
Addition of new features/functionalities	✕ Generally none, feature requesting may be available	✓ Development roadmap can be planned as needed
Data privacy	✕ Depends on vendor policy	✓ Data hosted internally, any own policy can be enforced

In today's social virtual world platforms market—including both the private and public sectors at a national as well as a European level—there does not seem to be any third-party option available as a service that can support the entire range, or even an acceptable subset, of the above minimum features and functionalities. In-house development, on the other hand, may, at first glance, seem more demanding and, even, intimidating than leveraging the ready-made feature set of an online virtual environment service. This is indeed true to an extent in the sense that programming, architecture and operations skills, as well as a solid theoretical background, are required. However, numerous benefits are guaranteed, by definition, with such an approach:

- The developer has full control of the entire lifecycle of the product, thus avoiding vendor lock-in, business model-derived restrictions, unforeseeable pivoting, etc.
- The product is hosted either in-house or on facilities fully managed by the developer.
- Content is also stored in facilities fully controlled by the developer and exclusively managed by them, which may be something desired or even required from a copyright and intellectual rights perspective.
- The overall cost is substantially reduced and more manageable.

These benefits together with the availability of numerous development aids such as those discussed above—to a far greater extent today than ever before—make the in-house development of a low TRL platform for recommendation purposes via the IMPULSE project, an appealing option.

7 Discussion and preliminary conclusions

As was stressed at the beginning of the deliverable, the WP2 of the IMPULSE project aims to identify technological solutions which can support the re-use of digitised Cultural Heritage content by Cultural Heritage Institutions in order to allow for further audience engagement. The context for re-use and presentation of the CH content is Metaverse platforms and related XR technologies. After taking into account the aforementioned challenges, the WP will investigate relevant technological solutions in order to provide recommendations towards creating a sustainable, decentralised, open access solution, which will support the reuse / recycling of already existing digitised Cultural Heritage content by Cultural Heritage Institutions, allow for further audience engagement, with the adoption of novel XR technologies and provide future policies that can be adopted by Cultural Heritage Institutions.

The examination of various virtual reality applications within cultural heritage contexts, conducted in this task, reveals a critical trade-off between the quality of graphics and the multi-user functionality. While high-quality graphics are a hallmark of many immersive experiences, they often cannot be adequately supported in multiuser and/or online environments. This limitation highlights a significant trade-off in the design of VR systems, where the pursuit of visual fidelity may compromise the ability to facilitate collaborative experiences among users.

Furthermore, most of the case studies indicate that user interactivity with content is generally minimal; while some applications allow for basic manipulations such as rotation or translation, more complex editing capabilities remain largely absent. This lack of user agency in content manipulation does not allow for the creative involvement of citizens in CH presentation and interpretation, nor does it work towards the democratisation of cultural heritage and the engagement of users with historical narratives. This is particularly important since IMPULSE aims to draw up recommendations for how to engage the audience of CH Institutions and enhance their agency.

Additionally, the investigation of selected implementations underscore the predominance of custom-made software solutions tailored to specific research projects, which often leads to enhanced functionality within the VR environments. However, this investigation also showed that very few cases have attempted a reappropriation of cultural heritage content into new contexts in order to achieve innovative reinterpretations that are relevant in the contemporary era. As the field of digital cultural heritage continues to evolve, addressing the challenges of user interactivity and the development of versatile, high-quality VR solutions will be essential for fostering richer, larger-scale and more inclusive engagement with cultural heritage.

Facial and gestural interfaces enhance social interaction between users in Multi-User Virtual Environments (MUVEs), while allowing for more natural and intuitive interactions between users and the virtual environment. Facial and gesture tracking technologies can map facial expressions and gestures onto avatars in real time, enabling users to express their feelings and emotions. This additional input in the VE improves non-verbal communication that is critical for effective social interaction and increases users' sense of presence and immersion in the virtual environment. Moreover, gesture recognition enables hands-free navigation and interaction within the virtual environment, making them more intuitive, natural and engaging. This feature makes VE more accessible to users with physical disabilities or users unfamiliar with standard VR interfaces. Facial recognition also contributes to the creation of personalised avatars that resemble the user's physical appearance. This way it could potentially support inclusivity and identity representation. Furthermore, gesture tracking and recording can be used for preservation and presentation of immaterial cultural heritage content such as rituals, traditional dances, and performances that can be captured and mapped onto avatars inside a virtual environment.

An overview of existing interactive technologies for social immersive VR indicates that it is currently possible to utilise a multitude of devices spanning a wide spectrum of interaction modalities in order to design and implement immersive experiences. These experiences can feature interaction that resembles face-to-face communication by allowing for the utilisation of nonverbal cues when interacting in the context of a social VR platform. However, more research is needed in order to highlight the ways in which such complex interaction processes can effectively enhance the User Experience of social immersive VR (and especially its "social" component). A more detailed look into the practice of integrating more advanced technologies (e.g. BCI) is also necessary in order to maximise the effectiveness and efficiency of the resulting solution. In any case, currently available head-mounted displays offer vastly increased specifications (e.g.

increased resolution, refresh rate, field of view) and provide a solid starting point for a robust and satisfying user experience of immersive social VR.

Regarding the potential of accessing content aggregators for enriching virtual worlds with new content, there are numerous Cultural Heritage content collections and repositories; however, the current landscape presents a number of challenges that need to be overcome in order to meet the goal of creating a truly accessible, standardised, and user-friendly ecosystem[93] that can serve researchers, educators, and the public alike. These challenges revolve around three primary axes: (i) fragmentation and the need for standardisation across multiple sources and on different levels, (ii) inconvenient access and lack of APIs, (iii) unintuitive interfaces and other technical issues (e.g. slow loading times) that detract from the User Experience. Among existing platforms, a detailed comparison revealed that Europeana and Sketchfab fulfil the needs of the project by offering robust API access. However, SketchFab is currently undergoing transformation and result of this process is uncertain. This is another indication that relying on existing proprietary platforms or content aggregators may prove to be problematic for IMPULSE, since the probability of support being rescinded in the future cannot be ruled out.

Therefore, custom development is probably a preferable option, both for addressing the differences in data structures and content types as well as for guaranteeing sustainability of access to the selected content aggregator.

With regards to the platform for supporting multi-user virtual reality, and taking into account the features for the platform that will need to be designed for the objectives of IMPULSE, there does not seem to be any third-party technology available as a service that can support the entire range, or even an acceptable subset, of the minimum features and functionalities, as these have been defined earlier in this document. In-house development however, may be more demanding than using the ready-made feature set of an online virtual environment service, but has numerous benefits such us:

- full control of the entire lifecycle of the product,
- hosting the product either in-house or on facilities fully managed by the developer,
- storing content in facilities fully controlled by the developer and exclusively managed by them,
- availability of numerous development tools and libraries.

Consequently, in-house development is indeed a feasible and appealing option for developing a low TRL platform, needed for the IMPULSE project.

[93] In accordance with the FAIR (Findable, Accessible, Interoperable and Reusable) principles

Finally, it has to be stressed that the review presented in this document, is by no means complete and finished, as sources will continue to be added to the references. WP2 will lead to the design and development of a pilot 1st version of a platform to support the activities of WP1 in the following months. Therefore, identifying a viable and optimum solution for creating this platform is an urgent need. However, the investigation of appropriate technological solutions to support the project's objectives will continue during the next stages of the project and will inform the phase of updating this platform and creating a 2nd version, that will also take into account user feedback, provided during the 1st pre-Hackathon activity. The ongoing nature of the review is in accordance with the dynamic and rapidly evolving context of digital technologies for Cultural Heritage.

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IMPULSE

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