Proceedings of the joint international event 9th ARQUEOLÓGICA 2.0 & 3rd GEORES, Valencia (Spain). 26–28 April 2021

Received: 27/11/2020
Accepted: 18/03/2021
DOI: https://doi.org/10.4995/Arqueologica9.2021.12109

THE ROLE OF EXTENDED REALITIES IN HERITAGE BUILDINGS REPRESENTATION

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Abstract:

Architectural visualisation has been developing over the year to improve the representation of buildings and their contexts to the public. It achieved a long journey from manual drawings to photography to digital 2D and 3D representation, until it reached the era of extended realities (XR), which allowed unprecedented immersive and interactive engagement. Extended reality applications represent a unique opportunity for the visualisation of heritage buildings on many stages; from the early design phase, through the construction and facility management phases, to the education and cultural tourism applications. This paper aims to explore the wide range of state of the art XR applications, investigate their aspects and variations, and study their potentials, challenges, and limitations for the built heritage sector.

Keywords: heritage buildings, visualisation, extended reality, virtual reality, augmented reality, mixed reality, HBIM

1. Background on Historical Building Representation

Architectural visualisation has been developing for a long time. It aims to present the building to a wider audience than its direct users. It can even represent the building in an iconic way, thus creating and exporting a symbolic image of a building, its context, culture, or place, even for audiences who have never visited the building itself. Historically, heritage documentation mainly relied on human interpretation such as hand drawings, on-site measurement, sculptures, and paintings, which was time-consuming and less precise (Albourae, Armenakis, & Kyan, 2017). The invention of photography in the early nineteenth century represented a revolutionary way to produce fast and realistic representations of buildings, as well as documenting their context and real-life view. Architectural representation, also, witnessed a revolution that transformed the manual analogue representation to the digital representation as a consequence of the introduction of CAD (Computer Aided Design) during the third industrial revolution in the 1980s (Techopedia, 2021; Banfi, 2019), which facilitated the transition into a digital 2D environment. This is shortly followed by the development of 3D visualisation software. The introduction of BIM (Building Information Modelling) tools further developed the ways of architectural representation in that it introduced an environment that can link several forms of buildings digital representation such as 2D drawings, 3D models, parametric information, photographic representation, and many other forms of data (Khalil, Stravoravdis, & Backes, 2020). Later, the introduction of extended reality applications and their rapid development paved the way towards a new era of immersive and interactive visual communication. It also helped to integrate more sensual and informative user-oriented experiences that can reach a much larger audience (Fig. 1).

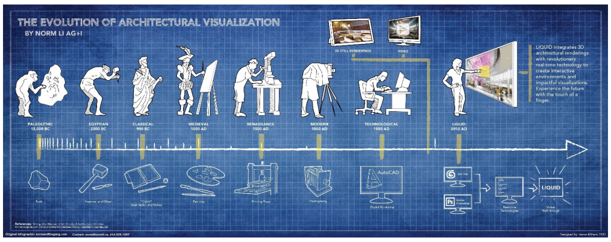

Figure 1: Evolution of architectural visualisation (Albourae, Armenakis, & Kyan, 2017).

2. Historical building representation in extended realities

Digital visualisation of heritage buildings and sites can represent a contribution for several aspects. it can help in planning preservation and conservation works by modelling and visualising the current status of the building and its historic view. It can assist in the process of adaptive reuse and retrofitting projects through better communication and visualisation through the design and construction phases. It can be a useful tool in real estate markets by marketing the building image for wider clients (Felli, Liu, Ullah, & Sepasgozar, 2018), which even gained

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more momentum due to the COVID-19 pandemic and its consequential social distancing strategies that shifted many markets towards the online digital environment. Also, digital visualisation plays a role in analytical researches concerning the building's history by modelling its various changes over time, as well as predictions of its potential future development (Fig. 2) (Rodríguez-Gonzálvez et al., 2017). Visualisation can also represent a revolutionary development in the fields of education, public dissemination, virtual museums and cultural tourism (Albourae, Armenakis, & Kyan, 2017)

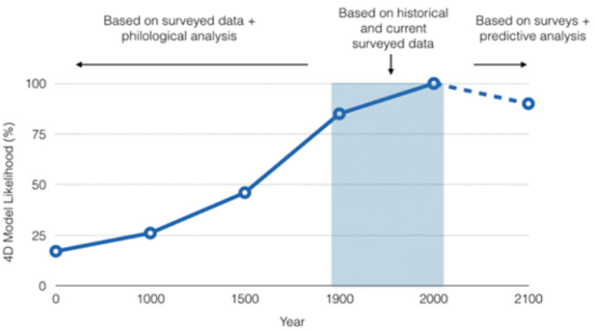

Figure 2: Representation of timeline in 4D visualisation (Rodríguez-Gonzálvez et al., 2017).

Digital visualisation of heritage buildings consists of many concepts involving the merging of physical real environment with digital virtual environment. It can be achieved through various levels of immersion and interactivity.

2.1. Reality/Virtuality

Visualisation and representation comprise of a wide spectrum of concepts, technologies and applications. The continuum containing all these applications is referred to as the reality/virtuality continuum, suggested by (Milgram, Takemura, Utsumi, & Fumio, 1995). It represents both the real world and the virtual environment on its two contrasting poles, while representing the different applications as levels of merging between them (Fig. 3). Following this classification, augmented reality (AR) is merging virtual objects into the real environment, mixed reality (MR) is half-way between real and virtual environments, while augmented virtuality (AV) merges real elements within the virtual environment, and virtual reality (VR) totally excludes the real world.

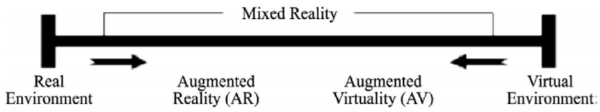

Figure 3: Milgram, Takemura, Utsumi, & Fumio (1995) Reality-Virtuality Continuum. The reality-virtuality continuum consists of environments ranging from real to virtual and all possible variations and compositions of real and virtual objects in these environments.

An umbrella term that is used to represent the whole spectrum including AR, MR, AV, VR and everything in between, is referred to as (XR) "Extended Reality" (Andrade & Bastos, 2019; Storchi, 2018) or "Cross Reality" (Davies, Miller, & Allison, 2013; Reilly et al., 2010; Paradiso & Landay, 2009), while Bekele, Pierdicca, Frontoni, Malinverni, & Gain (2018) used the term "Immersive Reality".

Bekele and Champion (2019b) argue that common definitions of Augmented Reality (AR), Augmented Virtuality (AV), Virtual Reality (VR) and Mixed Reality (MR) in current literature are based on outdated display technologies, and a relationship between virtuality and reality, without consideration to the importance of the users necessarily complicit sense of immersion. They conclude that existing definitions focus is technological, rather than experiential. Hence they redefined the reality-virtuality continuum according to the relation of different application to both the real world and the user experience (Fig. 4). Consequently, they classified the different visualisation approaches according to their level of fusion between real and virtual, the user interaction, the reality-virtuality interaction, and the level of immersion (Fig. 5).

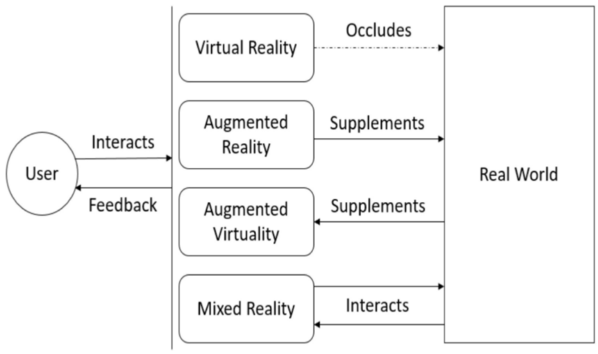

Figure 4: User-Reality-Virtuality (URV) Interaction: (Bekele & Champion, 2019b)

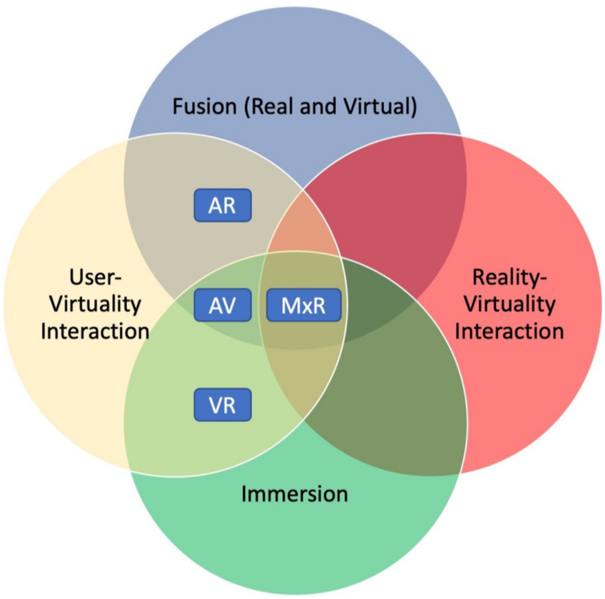

Figure 5: Classification of the different visualisation approaches according to (Bekele & Champion, 2019b).

2.2. Virtual Reality VR

Virtual Reality (VR) is defined as a segment of the reality-virtuality continuum that transports users into a computer-generated virtual world, where users are expected to experience a high level of immersion in the virtual environment (Carmigniani et al., 2011). VR is characterised by the fact that it immerses users in a synthetic world without any means to see or interact with the real world, except through computer-generated representations. the term "virtual reality" was first introduced in 1989 (Bekele, Pierdicca, Frontoni, Malinverni, & Gain, 2018). Immersion and interaction are key aspects of a VR experience. According to Carrozzino & Bergamasco (2010), VR is a complex technology that creates a digital environment with which users may interact and which they feel completely immersed within. This immersion can also include a simulation of visual perception, acoustic, haptic, smell, taste, and motion senses, A perfect virtual reality experience affects all of human senses and allows the user to interact with the virtual environment naturally as they would with the real environment (Bekele, Pierdicca, Frontoni, Malinverni, & Gain, 2018; Zhao, 2009).

VR, in conjunction with data capture technologies, provides many applications that are used for a variety of cultural heritage purposes, such as virtual museums, virtual reconstruction, virtual exploration, and Cultural Heritage education (Haydar, Roussel, Maïdi, Otmane, & Mallem, 2011; Gonizzi Barsanti, Caruso, Micoli, Covarrubias Rodriguez, & Guidi, 2015; Pietroni, Pagano, & Rufa 2013). VR can benefit from the development of 360° photography and videography to create virtual tours that can be useful especially in the field of real estate (Felli, Liu, Ullah, & Sepasgozar, 2018). VR also has the potential to simulate imaginative and existing physical environments along with their processes and environmental parameters (Bekele & Champion, 2019a).

Virtual reality can be presented in a 3DoF (Three Degrees of Freedom) or 6DoF (Six Degrees of Freedom) systems. In a 3DoF VR system, the user's head movements (rotation) are tracked, known as 'passive VR'; where the user can look but cannot control their physical movements in the space. In a 6DoF VR system, also known as 'active VR', the user's head and body movements are tracked (rotation and translation) (Dhanda et al., 2019). Slater & Wilbur (1997) stated that the correlation between user movements and the virtual movements is a crucial factor that affects how a user feels presence in a virtual space (Dhanda et al., 2019).

Photogrammetry and physically based rendering (PBR, a way of rendering that accurately represents how light interacts with materials and surfaces) can be used in modelling and representing VR (Dhanda et al., 2019).

Dhanda et al. (2019) have an interesting case study where they modelled the Myin-pya-gu temple in Bagan, Myanmar, which is no longer open the public due to its condition (Fig. 6). They used photogrammetry and laser scanning to capture the temple. Then a high poly mesh was created including 44 million polygons, which is too large to render in a real-time environment. Therefore, they reduced it to low poly mesh of 60 thousand polygons. They added mesh maps in order to enable the low poly mesh to realistically resemble the high poly mesh. Five types of maps are used in the PBR (physically based rendering); The texture map (holds all the colour information for the mesh), the normal map (use RGB values to encode surface normal directions.), the ambient occlusion map (approximates the inner shadows of objects when they are under diffuse lighting), the roughness map identifies the irregularities in a surface that cause light to scatter diffusely, and the metallic map (defines what part of the material are metal). Finally, the VR of Myin-pya-gu was put together in the Unreal Engine by Epic Games (Dhanda et al., 2019) (Fig. 7).

The main challenge facing VR applications to heritage buildings is in the modelling process and how to ensure the production of a photorealistic result with the least possible complicated model, in order to reduce rendering demands.

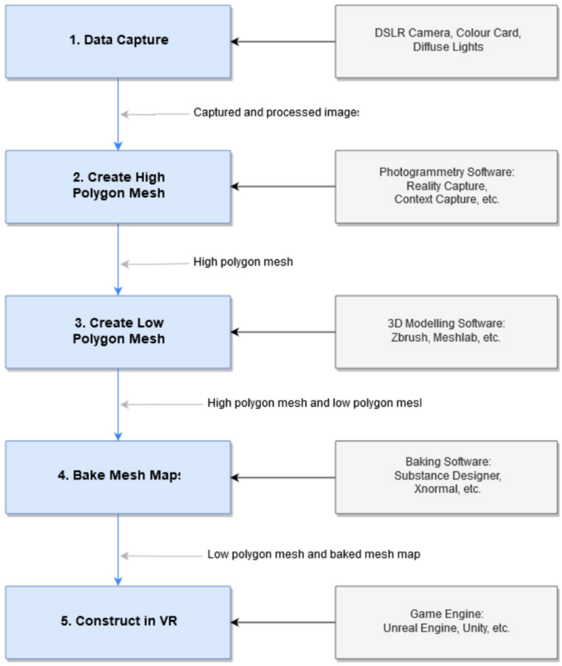

Figure 6: Workflow of the modelling of Myin-pya-gu temple (Dhanda et al., 2019).

Figure 7: VR model of Myin-pya-gu temple (Dhanda et al. 2019).

Another challenge facing virtual reality is Motion Sickness (MS) due to the high level of immersion, which causes general discomfort, apathy, drowsiness, headache, disorientation or fatigue users might feel during or after a VR experience. To induce motion sickness effects, complete surround environment with depth perception, spatialised audio, and natural gestures and movements should be achieved (Andrade & Bastos, 2019).

An interesting VR application is the reconstruction of the St Andrews cathedral in Second-Life platform by Davies, Miller, & Allison (2013). The reconstruction was used for viewing the original cathedral in a walking tour within the site of its ruins.

The 3D virtual environment was implemented using the Second Life/Open Simulator (SL/OpenSim) platform. A walking route around the St Andrews cathedral ruins, akin to the route that an individual visitor or school group might take, was planned and then walked with a laptop connected with GPS unit as well as a smartphone. Then real-world positions were translated as latitude and longitude pairs, into corresponding Open-Sim (X,Y). Information from the tablet's magnetometer and accelerometer were translated as joystick movement in the Second-Life platform to control the camera direction. Users can view the reconstruction of the cathedral following the defined route and point of interest (Fig. 8).

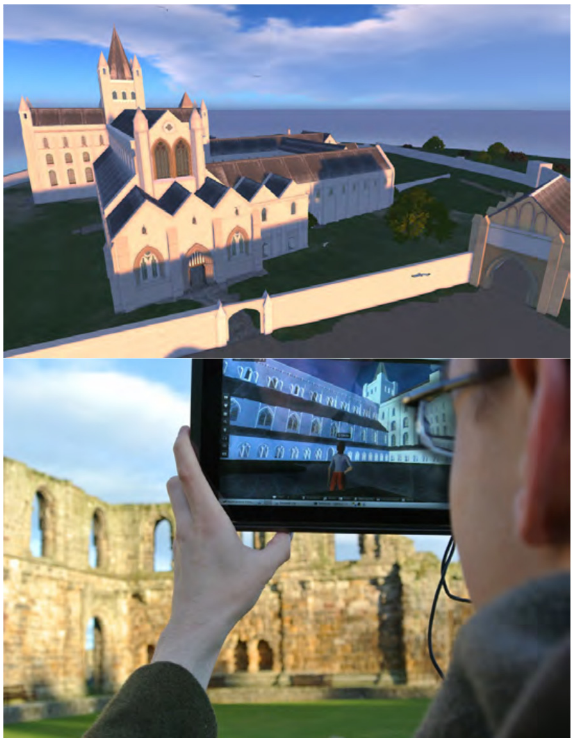

Figure 8: VR reconstruction of St Andrews Cathedral (Davies, Miller, & Allison, 2013).

In the context of historical buildings and VR, it is still a challenge to capture a building with high levels of detail and reproduce the experience in VR. It is technically possible, but normally experts from various disciplines are needed, such as 3D data capture, data processing and appropriate setup for VR which often involves programming in a game engine. All this can be costly and time consuming and as a result it is not easily scalable to be used for all buildings of historical significance. Low cost solutions such as the employment of inexpensive 360 degree cameras, the footage of which can be used directly in VR can provide an easy to employ, scalable solution for historical building VR experiences and digital presentation, but the current state of the art in this field lacks the level of detail needed. Recent technological updates to tablets and smart phones with Lidar sensors, show promise of an ability to easily capture and recreate environments in VR. This is a low cost, scalable solution, which is in the right direction, but its capabilities in the field are yet to be proven.

2.3. Augmented Reality AR

Augmented Reality (AR) is defined as a system that combines real and virtual contents. It provides a real-time interactive environment, and registers virtual objects in 3D to enhance the understanding of the physical environment (Azuma, 1997). According to (Milgram, Takemura, Utsumi, & Fumio, 1995), AR completes reality without completely replacing it. It aims to enhance the perception and understanding of the real world by superimposing virtual information on top of the real world view (Bekele & Champion, 2019a). Augmented reality is a collection of interactive technologies that merge these two elements; virtual and real, in real-time, providing accurate registration in three dimensions (Azuma, 1997). An AR system's typical characteristics are:

- It combines real-world and virtual objects.
- It runs in real time.
- It allows interaction between users and virtual objects (Azuma et al., 2001; Bekele, Pierdicca, Frontoni, Malinverni, & Gain, 2018).

The first AR device created was optical see-through, a Head-Mounted Display by Sutherland in 1968 (Marto & Gonçalves, 2019). In the cultural heritage applications, AR was adopted as early as 2001 with the ARCHEOGUIDE project (Vlahakis et al., 2001). AR allows the visualisation of no longer existing elements destroyed by human action or natural disasters, or, on the contrary, to hide successive addition revealing the original appearance of the investigated item (Leach et al., 2018; Sernani, Angeloni, Dragoni, Quattrini, & Clini, 2019). From the user's perspective, an AR experience overlays virtual information over their surrounding real environment. In order to fulfil this experience, the user should carry a technological device which allows to perceive virtual information, while seeing the real environment at the same time (Bae et al., 2016; Marto & Gonçalves, 2019). This can be used in three major application areas: enhancing visitors' experience, heritage reconstruction, and heritage data management and exploration (Bekele, Pierdicca, Frontoni, Malinverni, & Gain, 2018).

AR can serve in enhancing the visitors experience of heritage places by experiencing reconstructions of the building and its context at different historical periods, such as in the case of the project of 5G Smart tourism trial at the Roman baths in Bath, where over 100 visitors experienced reconstructions of the baths at key moments in history, on a mobile AR app. High-quality 360 video was streamed over the project's network, that included the first UK deployment of a 60GHz mesh network. (Fig. 9) (BBC R&D, 2021).

Outdoor AR experiences which attempt to embed 3D content into an environment are more complex than AR experiences inside buildings. Potential solutions are complicated by real world complexities such as dynamic environments (e.g. people and traffic movement and lighting changes) and solving the occlusion problem, i.e. showing a 3D model with some parts in front of and some parts behind different buildings. Specialist hardware, with depth cameras, can help, as can remote server power, but real-time SLAM (simultaneous localisation and mapping) is beyond consumer mobile phones for outdoor AR (Leach et al., 2018).

Augmented reality, while sharing with VR the need for high-end realistic, yet less computing capabilities demanding models, the main challenge is in the registration, alignment, and tracking process to produce seamless connection between the real world and the added virtual objects. This challenge not only relies on the modelling process but also on the viewing devices capabilities and tracking sensors.

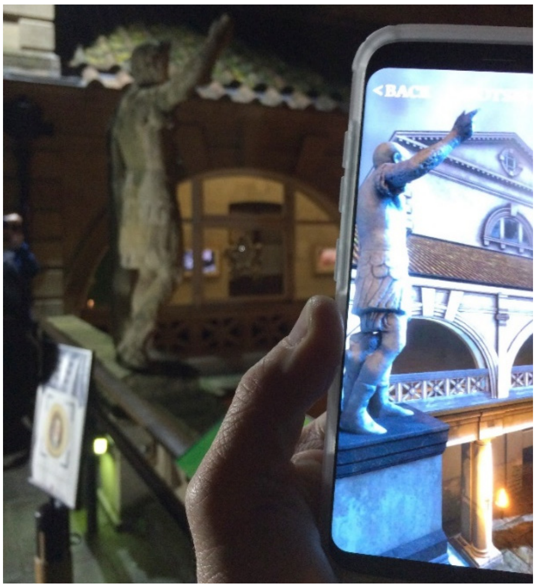

Figure 9: AR view of the Roman Baths in Bath in different historic periods (BBC R&D, 2021).

A case of AR application is the work of Leach et al. (2018) as they visualised Sheffield's medieval castle, destroyed during the English Civil War in the mid-seventeenth century, within its current location. They used outdoor AR system that run on android phones (Fig. 10). The process begins with the user alignment process to align virtual 3D model of the area containing various 'landmark buildings' with the real-world view, with the help of the smartphone the GPS and compass sensors (Fig. 11). Next is the viewing stage, where the castle is seen in situ using AR, correctly aligned and positioned relative to the user (Fig. 12). They are also considering modelling proposed future development of the area, so the users can view both the future building plans and the site's cultural heritage.

Program Flow (User Processes)	Data/Hardware Requirements
App Start (Press Continue)	– User Interface Icons
Alignment Screen (User lines up virtual landmark buildings with real world scene) (Press Aligned)	– GPS location – Landmark building photos – Known locations for landmark buildings – Gyroscope data – Accelerometer data

Figure 10: An overview of the components of the system (Leach et al., 2018).

The main limitation observed by the researchers was some drift issues over time, that can affect especially the depth masking process. although it can be rectified by user re-alignment, it could be more time consuming and interrupting experience for the user (Leach et al., 2018).

A project that combined VR and AR applications is in the work of Barazzetti & Banfi (2017) on the Castel Masegra, a castle located in the city of Sondrio (Lombardy region, Italy). A detailed and accurate HBIM was generated from laser scanning and photogrammetry, which provided a point cloud made up of 7.5 billion points. The different structural elements were modelled following their logic of construction as well as chronological, material, and stratigraphic aspects. The model was then simplified and exported into different file formats to try out different mobile applications for both professional operators and "casual" users interested in digital tourism.

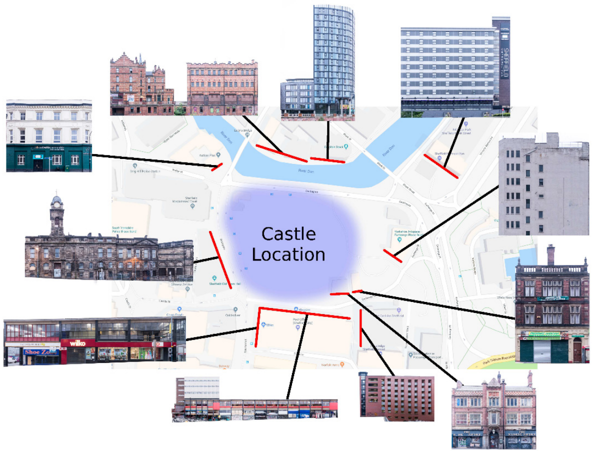

Figure 11: The various landmark buildings and their locations, which they used as markers for the AR mode tracking (Leach et al., 2018).

Figure 12: AR of the Sheffield castle with real surrounding buildings, modelled in front of the real Old Town Hall (left), and masked behind the real Market Tavern (right) (Leach et al., 2018).

The HBIM project of Castel Masegra (Autodesk Revit file format) was saved with the .dwf file format to preserve object information during the creation of the mobile version, so that the HBIM database remains available also in smartphones and tablets. A virtual tour of the castle was produced from the BIM model using iVisit 3D, which is based on the rendering engine Artlantis. AR visualisation on mobile phones was produced by AR-media application using markers in a brochure of the castle (Fig. 13). The main problem was in the transformation of BIM files into different formats for the visualisation that results in information loss.

Sernani, Angeloni, Dragoni, Quattrini, & Clini (2019) proposed the development of an AR app integrating image targets and SLAM to support and guide a visitor in the fruition of the "Studiolo" inside the "Palazzo Ducale" in Urbino, Italy. image targets are used to recognize the Points of Interest (POIs) and the SLAM to perform the object tracking and achieve a reliable immersive user-experience. SLAM can be used to anchor suggestions about different POIs into specific positions inside the "Studiolo", guiding the users' orientation during the visit. POIs were identified in the "Studiolo" to depict messages to the visitor that could not get many of them due to the high complexity of the scene and the need of a deep knowledge of Renaissance History, Literature, Philosophy and Policy. Then A linear storytelling was developed, from the entrance to the exit of the room, connecting all these elements.

Figure 13: BIM model of the Castel Masegra depicting chronological phases of the building that was used for mobile VR and AR applications (Barazzetti & Banfi, 2017).

When the image target is acquired in the AR, i.e. the POI is recognized, the app automatically switches to SLAM mode to perform instant tracking, assigning the visual elements related to the suggestion of other POIs to a virtual ground plane (Figs. 14 and 15).

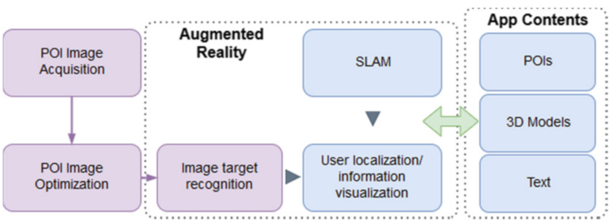

Figure 14: AR workflow of the “Studiolo” at “Palazzo Ducale” in Urbino, Italy (Sernani, Angeloni, Dragoni, Quattrini, & Clini, 2019).

Figure 15: Orthoimages of the POIs to be used as image targets for the AR app (Sernani, Angeloni, Dragoni, Quattrini, & Clini, 2019).

Limitation can occur in some challenging cases such as the change in ambient lighting, as well as the computational needs of SLAM that can stresses the mobile devices.

2.4. Augmented Virtuality AV

Augmented Virtuality (AV) aims to augment virtual environments with live scenes to enhance our understanding of the underlying virtual environment. This contrasts with VR’s aim to transport users to a completely virtual world. AV is closely aligned to AR in terms of purpose, in the sense that both aim at enhancing the environment they are applied to (Bekele & Champion, 2019a). However, AV applications to the built heritage are rather limited to date.

Gheorghiu & Stefan (2018) tried to implement AV to a visualisation of two Greco-Roman sites in Romania. They achieved it by adding architectural fragments reconstructed in reality (as experimental archaeology) and 3D-scanning of real characters dressed in epoch costumes into 3D models of the sites in order to enhance the users experience by adding information about activities and daily life technologies, in a living, engaging way (Fig. 16).

2.5. Mixed Reality MR

Milgram, Takemura, Utsumi, & Fumio (1995) defined Mixed Reality (MR) as *“...a particular subclass of VR related technologies that involve the merging of real and virtual worlds.”*. MR involves the blending of real and virtual worlds somewhere along the reality-virtuality continuum which connects completely real environments to completely virtual ones (Bekele & Champion, 2019a). According to Bekele, Pierdicca, Frontoni, Malinverni, & Gain (2018), Mixed reality is an environment where real and virtual content coexist and interact in real time. The aspects of augmented and virtual reality merge to achieve this. It is not just an alternative to augmented or virtual reality, rather, it is a unique perspective that enriches human perception of both real and virtual environments, where flexibility, immersion, interaction, coexistence, and enhancement are the essential aspects of a mixed reality experience. MR combines some properties from both segments, interactivity from AR and immersion from VR (Bekele & Champion, 2019a).

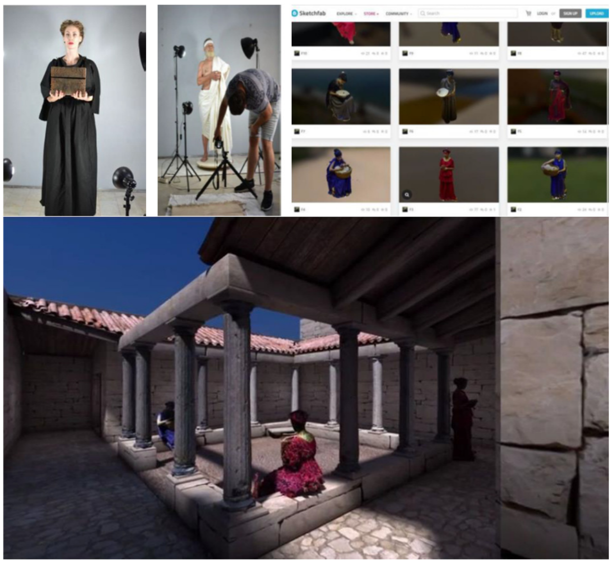

Figure 16: Adding real characters dressed in epoch costumes into virtual scenes (Gheorghiu & Stefan, 2018).

In contrast with MR, the academic literature has noted that AR has a limited visual and spatial immersion (Leach et al., 2018). MR, on the other hand, combines interactivity and immersion from AR and VR, respectively, to bring immersive-interactive experiences to our view of the real-virtual word (Bekele & Champion, 2019a).

MR applications for the built environment and specifically heritage buildings have been rare due to the lack of devices with robust real-time tracking, 3D registration, realistic virtual environments, natural interaction interfaces, and presentation devices for vivid experiences (Bekele, Pierdicca, Frontoni, Malinverni, & Gain, 2018). Over the past two years more and more MR devices are appearing in the market, such as Microsoft Hololens 2 (the first generation was released in March 2016 and the second generation in November 2019) (Microsoft, 2020) and Magic leap 1 (released in August 2018) (Magic leap, 2020). This is coupled with more built environment related applications. However, the focus is more towards the early design stage of buildings, but examples exist for building representation only. MR for heritage buildings has a lot of potential, but it is still not a straightforward process on how an existing heritage building can be meaningfully interacted with in MR, or how a digitally.

An interesting heritage related MR application is in the work of Pollalis et al., (2018) as they produced an MR visualisation and interaction with ancient Egyptian sculptures using the HoloLens 1 headset, 3D model viewing website (SketchFab), and plastic extrusion 3D prints (Fig. 17).

An example of MR application in facility management is in the "HeritageCARE" project by Fonnet, Alves, Sousa, Guevara, & Magalhães, (2017). The project is aiming to help facility management inspectors to inspect heritage buildings using Microsoft HoloLens. The idea is to impose a BIM model of the building on the real site in order to inspect and report any new problem (Fig. 18).

Figure 17: The 3D printed artefact inventory and Holographic artefact inventory used in MR visualisation by (Pollalis et al., 2018).

Drawbacks of the system are in the limited capacity of the HoloLens battery that is limited to 150minutes. Another problem is in the text input from the inspectors, as the HoloLens only allows a virtual keyboard which is not practical, so they rely on recording audio notes that require further time to translate into text notes.

Bekele (2019) suggested a framework for a walkable MR map that can allow users to interact with virtual objects via maps that are virtually projected on the floor and viewable through MR devices. The projected maps are room-scale and walkable with a potential global scalability. Besides movement-based interaction, users can interact with virtual objects, multimedia content and 3D models using Microsoft HoloLens's standard gesture, gaze and voice interaction methods (Fig. 19).

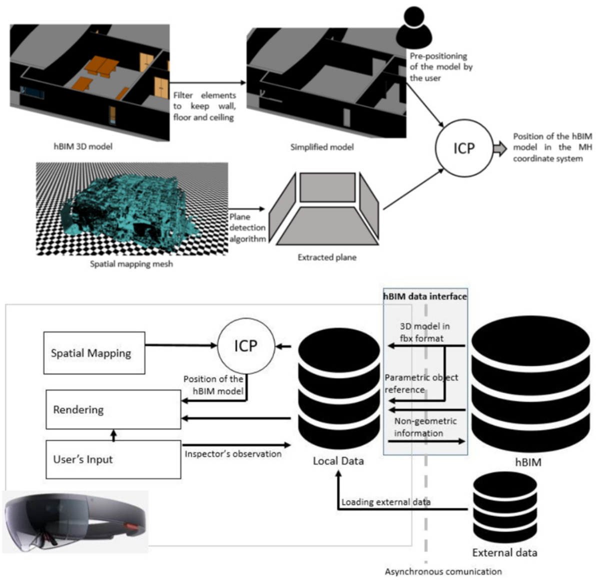

Figure 18: H-BIM model positioning steps and the architecture of the mixed reality application (Fonnet, Alves, Sousa, Guevara, & Magalhães, 2017).

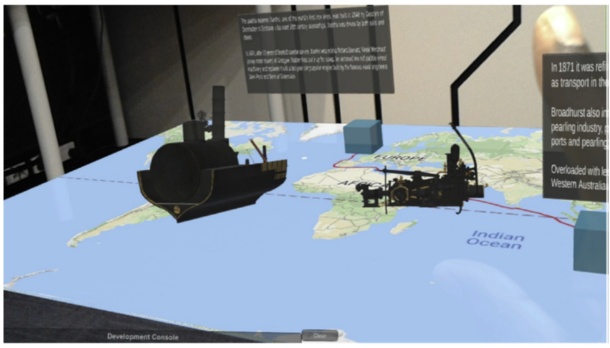

Figure 19: User moving round the map projected on the floor and interacting with 3D models placed on the map (Bekele, 2019).

The system consists of Head Mounted Display (HMD), Geospatial Information and Event Cue, Interaction Inputs and Mixed Reality Framework, Event and Spatial Query Handler, and Cultural Dataset containing historical and cultural context (3D models, multimedia content and event spatiotemporal information) (Fig. 20).

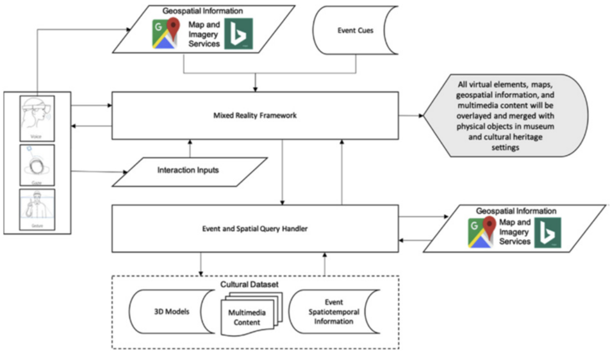

Figure 20: System architecture of the walkable mixed reality map (Bekele, 2019).

The map loads at the initial scene of that will be launched based on users' request. Once users start interacting with the virtual environment, a series of maps and 3D models and cultural context will be revealed to the user.

Limitations lay in the rapid development of software such as MRTK that are still going through rapid and frequent changes, which can cause some incompatibility issues with existing implementations and requires extra effort to port older version codes to latest version development framework. Another challenge is that rendering highly detailed 3D models in HoloLens is problematic, thus, the models had to be decimated to collapse the models to a less detailed and simplified geometry. Also, occlusion between physical and virtual objects can lead to some performance degradation, especially when there are moving objects continually detected by the environmental understanding cameras of the device. As a result, some lags were introduced when rendering frames.

2.6. Comparison

Different XR applications, while sharing the basic concept of visual representation of the building, can vary in many aspects. Figure 21 summarises the main aspects and their variations between the different extended realities, and explores their potential applications for the built heritage. Every aspect is represented in three levels (high, medium or low value). Every XR application for heritage buildings is represented in three levels (high potential, medium potential or low potential), this is based on how likely the specific application could benefit from each XR tool.

		AR	MR	AV	VR
Immersiveness		•	●	⬤	⬤
Photorealism		⬤	⬤	●	●
Interaction		●	⬤	●	•
Accessibility/ Ease of use		●	•	●	⬤
Technology		●	⬤	●	•
Heritage Buildings Potential Applications	Design	●	●	•	⬤
	Construction	⬤	●	•	•
	Facility management	⬤	●	•	•
	Real estate	•	•	•	⬤
	Education	●	●	●	⬤
	Cultural tourism	⬤	⬤	•	•
	Virtual museums	●	●	•	⬤

⬤ High value / high potential.

● Medium value / medium potential.

• Low value / low potential.

Figure 21: Aspects of extended realities and their potential applications for heritage buildings.

Immersiveness represents how much the user feels included in the virtual environment. Naturally, it is more observed in VR as the user is totally engulfed by the virtual environment and excluded from the real environment.

Photorealism, on the other hand, represents how realistic is the visualisation to the user experience. This is particularly harder to achieve in VR, as it depends entirely on the modelled virtual environment, in contrast with AR that basically uses the real environment as the main visualisation with virtual elements integrated.

Photorealism is defined by Ferwerda (2003) as one aspect of realism as they distinguished three different varieties of realism:

- Physical realism, where the virtual objects provide the same visual simulation as the real scene;
- Photorealism, where the image produces the same visual response as the scene;
- Functional realism, in which the image provides the same visual information as the scene.

It is argued that the non-photorealistic rendering (NPR) approach can also be used in AR to describe abstract information that is not representable, or in case of a required focus on a special detail (Haller, 2004). According to Fernando & Kilgard (2003) objects in wireframe, flat shading or NPR shading are easily discernible, and can focus the user's attention to augmented objects. Durand (2002) states that the border between photorealism and non-photorealism can be fuzzy and the notion of realism itself is very complex. He argues that the virtual world has to be interpreted as more convincing rather than realistic. The same idea is also elaborated by Roussou & Drettakis (2003).

Although, in the heritage sector, fine details are usually in need to be elaborated and models need to be rendered as realistic as possible with seamless integration of the virtual objects into the real world, In some cases non-photorealism could be of good use to differentiate different aspects, for example, to contrast different phases of the construction of the building using simplified models.

Interaction between the user and the visualisation environment and between the real and virtual environments is another aspect that varies between different extended reality applications. Mixed reality is considered as the ultimate interaction potential as it merges between real and virtual environments and enables users to interact with both environments and sometimes with other users through the virtual environment. Followed by the augmented reality that enables users to fully interact with their real surroundings and integrated virtual objects. VR, on the other hand, allows the user to interact only with the virtual environment. It includes, as well, two levels of interaction: 3DoF VR has very limited interaction as the user can only explore the virtual model, while 6DoF VR allows much more interaction as the user's movements are tracked and translated into the virtual environment.

Accessibility and ease of use favour VR applications as it requires only a medium of the display to view the visualisation and sometimes sensors for movement tracking without requiring the user to be in a specific location (i.e. the site of a heritage building) or to use an initial alignment and registration steps like in AR, MR, and AV.

The technology level required for visualisation varies as well. While VR is less complicated, AR needs more advanced technology to capture the real environment and align the virtual model within it using cameras and sensors for place, orientation, and movement registration and tracking. MR is even more technologically demanding as it requires interaction between the users and both real and virtual environment, it can also require fast communication technology to facilitate virtual interaction between different users in different places.

Extended reality can be used in a range of use cases that require specific applications. Visualisation in the design phase, for instance, can benefit from VR to visualise the proposed new design or alternative models. AR and MR can be used as well to view the new design within its actual location.

In the construction and facility management phases, AR is more appropriate as it visualises the building model and its different systems on the actual building. MR can potentially be useful in communication between different teams in the construction process.

In real estate marketing VR is the most useful tool as it can represent real 360° photos of the building as immersive virtual tours that are more appealing and informative to potential clients than photos and videos.

VR is also more likely as a potential tool for education, public dissemination and virtual museums to view heritage buildings in their different stages with linked information. MR and AV can also be helpful in education and virtual classrooms to facilitate communication between the presenter and audience with enhanced virtual and real merging.

Cultural tourism, on the other hand, has its ultimate potentials in AR and MR applications as models of lost buildings can be viewed within their actual places, also different changes and previous states can be viewed on the building's current status as well as linking useful information within the real view of the building.

3. H-BIM and extended reality in heritage buildings representation

HBIM tools represent a crucial development in the heritage buildings sector. It facilitates the integration of different stakeholders into a unified platform that can combine the various data about heritage buildings (Khalil, Stravoravdis, & Backes, 2020). HBIM can incorporate both quantitative assets (intelligent objects, performance data) and qualitative assets (historic photographs, oral histories, music) (Fai, Graham, Duckworth, Wood, & Attar, 2011), as well as historic texts, archaeological figures, architectural information, administrative data and past drawings, sketches, photos, etc. (Cheng, Yang, Bin, & Yen, 2015). HBIM offers a process of digitally documenting all the features that are made or incorporated into the heritage building over its life-span, therefore offers unique opportunities for information preservation (Albourae, Armenakis, & Kyan, 2017). HBIM is also useful to disseminate the building and its historic development for the wider audience through modelling the different phases of the building's history.

Extended reality applications can greatly benefit from HBIM environment as it already contains a detailed 3D model of the heritage building, enhanced with a multitude of data about the building. These 3D models can represent a base for different visualisation applications. Recent developments of visualisation engines such as Unity 3D engine and Unreal engine can link with BIM software to facilitate the transition from a BIM model to XR visualisation (Unity, 2021; Engine, 2020).

A recent development in the field of modelling and geometry capture is the introduction of applications for modern smartphones equipped with LIDAR sensors that can facilitate 3D geometric capture and upload it to create BIM models (Fig. 22) (Canvas, 2020). Although this approach is still in development and the accuracy of these models is still questionable, it has the potential to dramatically reduce the cost and time of geometry capture of heritage buildings and allows non-experts to perform a 3D capture of heritage buildings. This in turn can help to capture in 3D more heritage buildings with less cost and labour.

A similar approach is seen in the development of several online platforms that allow creating virtual tours and 3D photogrammetric models from lower end 360° cameras, such as Cupix (2018) and Matterport (2021) (Fig. 23).

These technologies can facilitate the introduction of VR and AR solutions for the heritage sector that can be beneficial in a wide range of uses from project collaboration to education to virtual museums to real estate. The significance of it is further emphasised in the situation of the current COVID-19 pandemic and the great shift from physical interaction to online interaction. Such technologies are removing barriers to the digital documentation of heritage buildings and provide new paradigms. It is easy to imagine a step by step approach that can be adopted by facility managers and other stakeholders in heritage buildings by 3D capturing one room at a time, as needed and as budgets allow without having to go through long procurement routes.

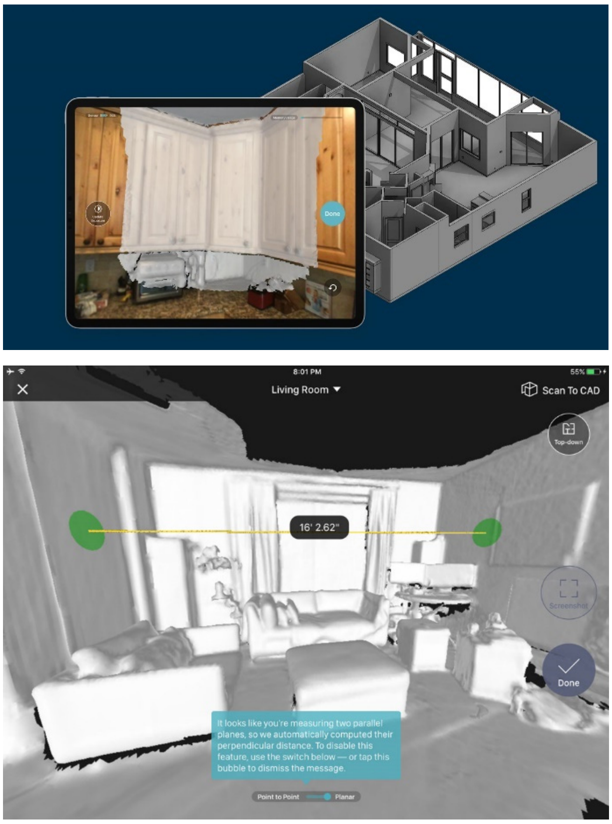

Figure 22: Canvas workflow that allows as built scanning using mobile devices equipped with LIDAR to create a BIM model (Canvas, 2020).

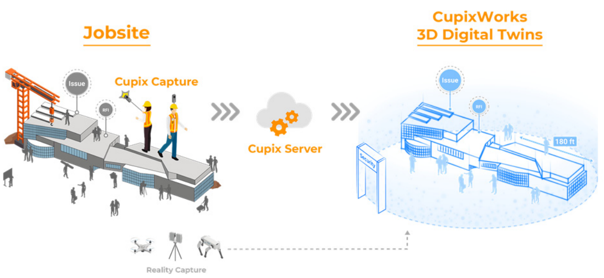

Figure 23: Cupix cloud-based workflow using 360° photography to create as-built photogrammetric models (Cupix, 2018).

4. Conclusion

Heritage buildings digital visualisation is an area that witnessed a revolution in architectural representation through extended reality applications. It can facilitate faster and more reliable communication between project's stakeholders, as well as creating more immersive and interactive public engagement and education about built heritage.

Extended reality (XR) is represented in a spectrum that merges real environment and virtual environment. It contains, augmented reality (AR), mixed reality (MR), augmented virtuality (AV), and virtual reality (VR). They differ in their respective level of immersiveness, photorealism, interaction, ease of use and technology.

VR, as the most basic form, totally excludes the real world and represent the most immersive experience. It can be used to present buildings that could be lost, damaged, or not accessible. The major challenge in VR is how realistically the building can be modelled to enhance the immersion of the user. The great potentials in VR are in the straightforward user experience (with no requirement of registration and alignment), it can be viewed on a wide range of devices and can be experienced in any place. Even the higher-end VR devices are in constant development and rapid drop in cost, which can contribute towards more public accessibility.

AR, on the other hand, aims to represent a building, element, or information within the real world. It can also present planned works within its actual real environment. It can represent lost historical elements or buildings within their actual site or show how the building looked in previous times. Beyond the modelling challenges, AR faces the registration and tracking challenges, to keep the modelled part aligned within the real view, where many sensors can be used to achieve it. This means that, although it can be accessed on average smartphones, it requires a high level of sensor responsiveness and computing capacity. Potential mobile devices with some kind of SLAM technology (simulations location and mapping) could be of great benefit in AR applications for heritage buildings.

In the same way, AV is where the virtual environment is augmented with real elements, however, its application is rather limited in the built heritage.

Whereas, MR is the ultimate merging between real and virtual environments. it depends on the fast advancement of communication and display technologies. It is still an area in development; however, it promises the most interactive and engaging experience, which can be an added value for the representation of heritage buildings.

Extended reality applications represent valuable potentials for the heritage sector. It can enhance the visual representation in the design process. AR and MR applications can also serve as a communication tool between different teams in the construction phase to better monitor progress and conflicts on the real building, as well as helping in helping in the facility management process.

Virtual reality can be used in real estate marketing, education, and virtual museums application. While augmented reality can be a very useful tool in cultural tourism to add valuable information to real-life views as well as viewing the past status of the building and its context.

Limitations of the extended reality applications are mainly represented on its dependability on high-end technologies, sophisticated devices, reliable software, fast communication systems, and complicated workflows, which makes it harder to achieve, especially to produce photorealistic, low-latency, immersive user experience. Although constant development in technology is leading the way towards wider XR applications with better results, it can mean also that older models can no longer be accessed with newer technologies, which is a challenging aspect in the heritage sector that ideally requires visual models to live longer and be viewed for long times. Adding to that, that the heritage building sector is typically more expensive to run and less in revenue than other projects, as a result, the financial capabilities for extended reality application could be limited, especially to update models every few years or even months to follow up with the endlessly developing technologies, software, and viewing devices.

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