A Survey of Augmented, Virtual, and Mixed Reality for Cultural Heritage

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A multimedia approach to the diffusion, communication and exploitation of Cultural Heritage (CH) is a well established trend worldwide. Several studies demonstrate that the use of new and combined media enhances how culture is experienced. The benefit is in terms of both number of people who can have access to knowledge and the quality of the diffusion of the knowledge itself. In this regard, CH uses augmented, virtual and mixed reality technologies for different purposes, including education, exhibition enhancement, exploration, reconstruction and virtual museums. These technologies enable user-centred presentation and make cultural heritage digitally accessible, especially when physical access is constrained. A number of surveys of these emerging technologies have been conducted, however, they are either not domain-specific or lack a holistic perspective in that they do not cover all the aspects of the technology. A review of these technologies from a cultural heritage perspective is therefore warranted. Accordingly, our paper surveys the state-of-the-art in augmented, virtual and mixed reality systems as a whole and from a cultural heritage perspective. In addition, we identify specific application areas in digital cultural heritage and make suggestions as to which technology is most appropriate in each case. Finally, the paper predicts future research directions for augmented and virtual reality, with a particular focus on interaction interfaces and explores the implications for the cultural heritage domain.

CCS Concepts: •**Computing methodologies** → **Mixed / augmented reality; Virtual reality;**

Additional Key Words and Phrases: Cultural heritage, augmented reality, virtual reality, mixed reality

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1. INTRODUCTION

Cultural Computing (CC) is an emerging field that applies computer technology and scientific methods to culture, arts, and the social sciences in order to represent, enhance, extend, and transform creative products and processes [Wang 2009; Haydar et al. 2011]. Advancements in computer technology have made the acquisition, recording and manipulation of 3D data technically achievable [Portalés et al. 2009] with techniques such as reverse engineering and computer graphics being used for analysing, studying, preserving and visualising Cultural Heritage (CH) assets [Barsanti et al. 2015]. In the last decade the use of enabling technologies in Cultural Heritage has been extended to immersive technologies - a collective term for augmented, virtual and mixed reality technologies, which provide sensory experiences through various combinations of real and digital content.

Cultural heritage, as a domain, benefits significantly from the use of these technologies. Users are able to experience cultural artefacts in a completely new way. While there are a number of general surveys of immersive reality technologies [Azuma 1997; Azuma et al. 2001; Papagiannakis et al. 2008; Zhou et al. 2008; Zhou and Deng 2009; Costanza et al. 2009; Van Krevelen and Poelman 2010;

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Carmigniani et al. 2011; Adhani and Awang 2012; Arth et al. 2015; Sanna and Manuri 2016; Anthes et al. 2016] there has been little attempt to collate and analyse the available literature on their application to the Cultural Heritage domain specifically. In addition, there is no comprehensive review of the research challenges or future directions in this area. Such a review is called for given that recent literature provides a plethora of new applications aimed at enhancing the perception of art through digital content and new interaction mechanisms. Our survey fills this niche and is intended to help researchers, practitioners, art curators and developers understand the benefits and potential hurdles of applying immersive reality to Digital Cultural Heritage.

The impetus to exploit different forms of digitization in the CH domain dates back decades. It has even been made explicit in EU commision policies that the democratization of goods that have value for all humanity should be ensured through digitization, accessibility and interoperability, in order to enable sharing of both information and resposibilities aimed at conserving cultural identity and awareness

Digitization enables the spread of knowledge, and the use of innovative immersive reality tools could further facilitate the access to CH in a more appealing and innovative way. The only surveys specifically from a CH perspective cover virtual museums [Styliani et al. 2009], virtual reality for tourism [Guttentag 2010], mobile AR applications for CH communication [Casella and Coelho 2013], and the challenges of AR for CH [Noh et al. 2009; Kounavis et al. 2012; Rigby and Smith 2013]. A more holistic view of the field is therefore warranted. This review provides practitioners with all factors that need to be considered when determining technology adoption and the relevant technical requirements for a range of CH applications. Hence, the main objectives of this review are:

—to outline state-of-the-art research and applications of Augmented, Virtual and Mixed reality for the CH domain;
—to reveal areas of research concentration and deficiency in this field, thereby highlighting limitations of existing technology and impediments to future research;
—to provide a framework for comparing state-of-the-art systems, in order to understand which solutions are most appropriate for a given application;

Thus, in this paper we survey the essential aspects and the current state-of-the-art in augmented, virtual and mixed reality from a CH perspective and describe research performed to develop applications and systems. We further summarise the adopted technologies and application areas of these studies and suggest future research directions. The remainder of the paper is organized as follows: Section 2 describes the reality-virtuality continuum and provides the most accepted definitions of augmented, virtual and mixed reality. Then Sections 3 provides a detailed discussion of the enabling technologies of these immersive reality approaches from a CH perspective. Section 4 evaluates the major CH-related works and identifies application areas, with a focus on the last decade, and provides technical requirements for the identified areas. Current issues and future research directions are outlined in Section 5. Finally, Section 6 provides a concluding summary.

2. THE REALITY-VIRTUALITY CONTINUUM

The reality-virtuality continuum describes the span between real and virtual environments, with Augmented Reality (AR) and Augmented Virtuality (AV) in between [Milgram and Kishino 1994]. AR is close to the real world and AV is close to a virtual environment [Milgram et al. 1995], as shown in Figure 1.

Augmented reality's most accepted definition was provided by Azuma [1997] as "a system that combines real and virtual content, provides a real-time interactive environment, and registers in 3D." According to [Milgram and Kishino 1994], AR completes reality without completely replacing it. AR

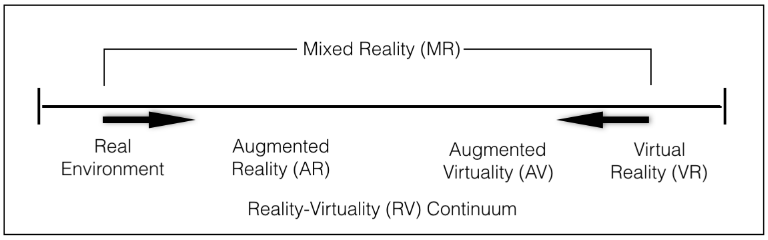


Fig. 1: The reality-virtuality continuum consists of environments ranging from real to virtual and all possible variations and compositions of real and virtual objects in these environments.

studies performed in the last decades, however, have shaped the definition of AR as a system that enhances our view of the real world by adding virtual and computer generated information [Rolland and Fuchs 2000; Vlahakis et al. 2001; Liarokapis et al. 2005; Haydar et al. 2011; Casella and Coelho 2013]. An AR system typically has the following characteristics [Azuma et al. 2001]: i) it combines real world and virtual objects, ii) runs in real-time, and iii) allows interaction between users and virtual objects [Liarokapis 2007]. Beyond this, Azuma [1997] extends the concept of AR to systems with the potential to remove objects from a real environment using graphic overlays—some scholars classify this as Mediated Reality. In general, both augmented reality and mediated reality aim to enhance our perception of and interaction with the real environment by adding virtual information and providing intuitive interaction metaphors. However, the former adds virtual information over the real world view and displays an augmented view, whereas the latter overlays synthetic content to cover or virtually erase the real world view or some part of it. Since it is similar to AR, mediated reality can be placed close to the real environment in the continuum.

Virtual Reality (VR), on the other hand, when fully exploited, completely immerses users in a synthetic world without any possibility of seeing the real environment, except through computer-generated representations [Carmigniani et al. 2011]. VR provides synthetic content to the senses in such a way that visual perception, hearing, and touch approach the experience of an actual environment [Zhao 2009].

The third approach Augmented Virtuality (AV) augments the virtual world with live scenes from the real world. Mixed Reality (MR) covers the continuum from AR to AV and aims at blending the real and virtual environments in different ways. It is thus a broad category covering various forms of AR and AV in a single technology.

While there is no generally accepted collective term for all these technologies, we will use Immersive Reality when referring to any or all of VR, AR and MR.

Providing a fine distinction between AR, AV, VR and MR is beyond the scope of this survey paper. However, we provide the following simple working definitions for the continuum.

—Augmented Reality (AR): aims at enhancing our perception and understanding of the real world by superimposing virtual information on our view of the real world.

—Augmented Virtuality (AV): aims at augmenting the virtual world with scenes from the real world.

—Virtual Reality (VR): aims at enhancing our presence and interaction with a computer-generated environment without a means to interact with or see the real world.

—Mixed Reality (MR): aims at blending real and virtual environments.

3. IMMERSIVE REALITIES AND CULTURAL COMPUTING

A number of studies demonstrate the viability of augmented, virtual and mixed reality adoption for different application areas in CH [Dow et al. 2005; Chrysanthi et al. 2012; Pietroni et al. 2013; Kang 2013; Barsanti et al. 2015]. In terms of AR, recent applications, such as the ARCHEOGUIDE project [Vlahakis et al. 2001] show its relevance to the cultural computing domain, and Arcese et al. [2011] predict the further spread of AR in the CH sector. These studies show that Augmented Reality is appropriate in the context of Cultural Heritage. Based on these investigations and other applications developed by researchers, such as [Zoellner et al. 2009b; Kim et al. 2009; Colizzi et al. 2010; Damala et al. 2012; Rattanarungrot et al. 2014; D'Auria et al. 2015], the three major application areas of AR in CH are: enhancing visitors' experience, heritage reconstruction, and heritage data management and exploration.

Even though the adoption of VR in a wide spectrum of application domains began soon after the term "virtual reality" was introduced in 1989, there has since been a variety of interpretations of the term [Zhou and Deng 2009]. The technological and immersive aspects of VR have contributed to the diversity of definitions. However, mediating among the technology and immersion-centered assertions, Carrozzino and Bergamasco [2010] properly defined VR as a complex technology that creates a digital environment with which users may interact, and which they feel completely immersed within. Thus, immersion and interaction are essential aspects of a VR experience. In a narrower sense, since visual information tends to override all the other senses, immersion implies that the visual aspect of the experience is the ultimate sensory effect of VR. Ideally immersion, however, also includes a simulation of acoustic, haptic, smell, taste and motion senses. A perfect virtual reality experience affects all of our senses, and allows us to interact with the virtual environment naturally—as we would with our surrounding real environment. Though VR aims at enhancing one's presence in a virtual environment, which is a cumulative effect of immersion and interaction, it does not necessary imply that the digital environment is a representation of a fictitious world. Instead, researchers in the CC domain have exploited VR and 3D data acquisition techniques such as photogrammetry and laser scanning to build applications that are used for a variety of CH purposes, such as virtual museum, virtual reconstruction, virtual exploration, and cultural heritage education [Gaitatzes et al. 2001; Mourkoussis et al. 2002; Christou et al. 2006; Haydar et al. 2011; Pietroni et al. 2013; Barsanti et al. 2015]. Section 4 discusses these application areas, in detail.

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. MR is not just an alternative to augmented or virtual reality. Rather, it is a unique perspective that enriches humans' perception of both real and virtual environments. Flexibility, immersion, interaction, coexistence, and enhancement are the essential aspects of a mixed reality experience. It is achieved by adopting the technological aspects of both AR and VR. Thus, an MR experience, regardless of the domain, provides a real-virtual environment, where users feel immersed and their perception of the real world is enhanced. Mixed reality systems in the CH domain include the studies by Hall et al. [2001], Galani [2003], Benko et al. [2004], Magnenat-Thalmann et al. [2004], Magnenat-Thalmann and Papagiannakis [2005], Dow et al. [2005], Liarokapis et al. [2007], Naemura et al. [2010], Santos et al. [2010], Chrysanthi et al. [2012], Oliva et al. [2015], and Okura et al. [2015].

Regardless of the domain, the essential aspects of augmented, virtual and mixed reality applications are:

—*Tracking and registration*

—*Virtual environment modelling*

—*Computers, display, and devices for input and tracking*

—*Interaction interfaces*

A particular immersive environment *system* is formed by making different choices for these components and certain pre-packaged options are available as part of existing *development tools*, which serve to accelerate system development.

3.1 Tracking and registration

Although both AR and VR applications seek to track the user's viewpoint, their ultimate purpose is different. AR needs tracking to superimpose virtual content over real environment views, while in VR the purpose is to correct the perspective of displayed virtual content. Unlike AR, tracking is not a must in VR applications, unless the experience is intended to be immersive. For instance, a desktop or mobile non-immersive VR system can display virtual content without tracking the user's pose. As with AR, tracking in Mixed Reality is needed to seamlessly register virtual content and real-world views in real-time and correct the perspective to enhance users' presence in the real-virtual environment. It is important to distinguish between calibration and tracking; the former refers to determining an initial viewpoint and camera properties, while the latter refers to continuous re-evaluation of poses to accurately align assets [Rigby and Smith 2013]. The practical effectiveness of registration is highly dependent on a tracking method's speed and accuracy.

There is a broad divide in tracking between techniques that rely on a camera as opposed to using physical sensors. For augmented reality applications in the CH domain, tracking is usually achieved by camera-based techniques (marker-based, markerless, or infrared) [Bay et al. 2005; Zoellner et al. 2009a; Seo et al. 2010], sometimes supplemented by sensor-based electromagnetic or hybrid tracking methods. There are also many ways to achieve positional tracking in VR, but they tend to rely more on sensor-based electromagnetic, acoustic, inertial, and hybrid tracking. One exception to this trend is the widespread use of camera-based IR tracking. MR applications use similar methods to achieve tracking.

3.1.1 *Camera-based.*

Marker-based tracking. Marker-based tracking uses a digital camera, vision algorithms, and easily recognisable landmarks placed in indoor or outdoor environments—these fiducial markers could be passive (printed markers) or active (IR emitting), with the latter discussed in more detail later. Most of the existing AR applications use passive markers. However, such a tracking approach is less suitable indoors, because markers generally require good lighting condition, although such lighting conditions can be controlled. More importantly due to CH fragility, markers may not be usable due to the possibility of damage. Nevertheless, placing markers in indoor conditions is technically affordable, for instance, the ARCO project [Wojciechowski et al. 2004] uses markers to display and remove virtual objects (3D models) into and from the AR environment. Users are able to interact with the virtual objects using the markers. In another project, MARCH, [Choudary et al. 2009], visual makers—in the form of coloured patches—are used to superimpose virtual objects over digital cave images. The marker-based tracking methods employed in these projects are in indoor conditions. However, the former uses fiducial markers while the latter uses visual markers.

Markerless tracking. Vision-based tracking (also called *markerless*), generally, tracks camera pose by detecting and recognising geometric features in the real environment to establish 3D world and 2D image coordinate correspondences. This approach can provide realistic real-time camera pose tracking. However, rendering virtual objects over the real environment could be slow due to the large amount of processing required [Papagiannakis et al. 2008]. Unlike marker-based techniques—which are dependent on easily recognisable markers, markerless tracking depends on distinguishable geometrical features, such as building corners and edges.

In computer vision, most tracking techniques can be divided into two classes: *feature-based* [Cucchiara and Del Bimbo 2014] and *model-based* [Uchiyama and Marchand 2012]. The underlying concept of *feature-based* methods is to find a correspondence between 2D image features and their 3D world frame coordinates. *Model-based* techniques, instead, explicitly use a model of the features of tracked objects such as a CAD model or 2D templates of the object based on distinguishable features. The tracking phase is based on lines, edges or shapes present in the model.

This tracking approach can be used for both indoor and outdoor AR applications. However, it is not always feasible if the site lacks suitable features and the model-based approach requires a database of images, for each object in the real environment, taken from different viewpoints. Moreover, markerless tracking is more prone to failure under conditions where the motion frequency of a camera is high—geometric features may not be detected at all or virtual objects could be miss-registered.

More recently the Kinect has been used to establish 3D world and 2D image correspondences to determine camera pose, thereby demonstrating that the combination of depth and image correspondence can provide reliable estimates of camera pose [Bostanci et al. 2015]. When compared with marker-based approaches, markerless tracking has the potential of being used for both indoor and outdoor AR applications as long as the database of images of the real environment is in place. However, this approach suffers from significant processing requirements, which often introduces registration delay.

Infrared (IR) tracking. Optical infrared (IR) tracking is a method of estimating in real-time the pose of a given target by tracking the position and orientation of either active or passive IR markers. The two basic characteristics that differentiate this tracking are: it always uses IR markers and is not affected by lighting conditions. Active markers are IR emitting diodes that periodically flash IR light, whereas passive markers consist of retro-reflective materials that reflect back the incoming IR lights towards the source. Usually multiple cameras illuminate the tracking space with IR light, thereby allowing the 3D location of multiple targets to be measured. Here, it is worth distinguishing between measuring the position of a target and measuring the pose of a target. With a single marker attached to a target only its position can be tracked. Multiple markers are needed to track both position and orientation. IR tracking has low latency, however, it does not function if the line of sight between the IR source and retro-reflector is obscured. Such systems can also be affected by ambient IR radiation present in the tracking space. Haydar et al. [2011] and Barsanti et al. [2015] use IR tracking in their respective VR cultural heritage systems—the latter combines optical and inertial tracking methods to obtain robust pose tracking performance.

3.1.2 *Sensor-based.*

Electromagnetic tracking. Electromagnetic tracking relies on measuring the intensity of the magnetic field between a base station and a measurement point, in various directions and orientations. The strength of the magnetic field determines distance, and the distributional change along various axes—caused by rotating the measurement point— determines orientation. This tracking system has low latency and high responsiveness, but it is subject to interference from other magnetic fields near the tracking space. However, this can be mitigated by installing the tracking system in a controlled environment. Gaitatzes et al. [2001], in their project “Reviving the past”, use electromagnetic tracking devices attached to an HMD, to track museum educator’s pose to provide a corrected perspective of displayed images.

Acoustic tracking. Acoustic tracking estimates the pose of a viewpoint by calculating the time taken for ultrasonic sound waves to travel from a target (emitter) to a sensor, which is usually kept stable in the tracking space. Ultrasonic emitters are attached to the HMD and interaction devices, if both the viewpoint and interactions are being tracked. When multiple sensors and emitters are present in the tracking space, the time difference between the ultrasonic waves travelling through synchronised sensors and emitters provides an estimate of the orientation of the sensors relative to the emitters. Unfortunately acoustic trackers have low update rates as a result of the relatively slow speed of sound. Moreover, this tracking system is prone to measurement errors caused by ambient noise. Acoustic tracking systems provide a better accuracy when fused with other tracking methods. For instance, Hernández et al. [2007], combine acoustic and inertial tracking for a cultural heritage VR application—the authors present an immersive VR system that allows users to physically walk and track their pose while they are exploring a virtual environment.

Inertial tracking. Inertial tracking is a navigation system that uses gyroscopes and accelerometers to measure the rotation and motion of a given target, thereby enabling the calculation of pose and velocity. The accelerometer measures linear acceleration to calculate the position of a target relative to some initial point. The gyroscope, on the other hand, measures angular velocity to calculate the angular rotation of a target relative to some initial orientation. Hence, the pose of a target is the integration of the measurements from the accelerometer and the gyroscope. This tracking method is inexpensive and can provide high update rates with low latency. However, it suffers from positional drift as a result of the accumulation of small measurement errors from the accelerometer and the gyroscope. Thus, relying on inertial tracking alone to estimate the position is problematic. An alternative is to fuse it with other tracking methods to obtain better positional accuracy, for instance, Hernández et al. [2007] combine acoustic and inertial tracking methods, and Barsanti et al. [2015] combine optical and inertial tracking.

3.1.3 *Hybrid tracking.*

. A fusion of the aforementioned tracking methods can yield better results than when each of them are employed separately. For instance, inertial tracking suffers from positional drift but provides better accuracy for orientation measurement, and marker-based and IR tracking are affected if markers are occluded. During such situations the data from the inertial tracker is used to estimate position until camera-based tracking is synced to the marker again. In particular, inertial tracking is often combined with the other tracking methods. Also relevant is the work of Vlahakis et al. [2001], which uses Kinect to establish 3D world and 2D image correspondences and, from them, determine camera pose.

There is also a trend to combine GPS and camera-based tracking, which is a good solution in cases where the POIs are very close to each other (e.g. in a big city). With the help of the picture taken by the camera and the GPS coordinates, the device can recognize attractions in a more flexible and reliable way [Attila and Edit 2012]. Additional insights about this approach are reported by Geiger et al. [2014].

Typical applications, in the CH domain, that use hybrid tracking include [Vlahakis et al. 2001; Schnädelbach et al. 2002; Miyashita et al. 2008]. For instance, the ARCHEOGUIDE application, [Vlahakis et al. 2001], combines markerless tracking and GPS to determine viewpoint pose.

3.2 Virtual environment modelling

In a broader sense, virtual environment modelling is the process of simulating real objects and their state in a digital space, the behavioral rules that the objects obey, and relationships and interactions between them [Zhao 2009]. To this end, there are several types of model data and modelling methods.

3.2.1 *Model data types.* Data acquisition methods and the aspects associated with real world objects are the two broad perspectives used to classify data types. From a data acquisition perspective, there are three types of model data, namely, actual measurement, mathematical measurement, and artificial construction [Zhao 2009]. Actual measurement refers to the model data acquired through the processes of 2D and 3D scanning, and any other process that involves the use of data capturing equipment. For instance, Barsanti et al. [2015] use photogrammetry to acquire the 3D data of ancient Egyptian artefacts—a wooden sarcophagus and heart scarab—and model them for VR visualisation. Mathematical measurement refers to the use of mathematical models, abstractions, and experimental analyses to generate model data of the real environment. The model data from both actual and mathematical measurement represent the real word in digital space, although they use different techniques to acquire the model data. Artificial construction, however, refers to model data generated by human imagination, where the world represented by the model data is completely fictitious. Since the virtual environment in most CH-based VR applications are representations of the real world, actual measurement techniques, such as photogrammetry and laser scanning, and mathematical measurement methods are most often employed.

In terms of real-world associations, model data types can be categorised into spatial structure data, physical, behavioural, and dynamic properties, and motion data [Zhao 2009]. Spatial structure data refers to the geometric state of real objects; physical property data describes the physical processes and changes of real objects; behavioural property data represents the behavioural processes of real objects; and both dynamic and motion data describe the real objects' deformation, collision, motion, etc. Despite this range, in practice VR systems in the CH domain tend to focus primarily on spatial structure data to represent the geometrical aspects of artefacts and use actual and mathematical measurement methods for data acquisition.

3.2.2 *Modelling methods.* Modeling methods can be classified according to the perception modalities of the intended user and aspects of the simulated objects in the VR environment. Accordingly, from a sensory perspective, modelling methods are classified into visual, auditory, and haptic. From the simulated object perspective, on the other hand, the modelling methods are categorised into scene appearance, physics-based behaviour, and real-virtual combined modelling [Zhao 2009]. Of these, scene appearance and real-virtual combined modelling methods are common in cultural heritage VR applications, because the former focuses on representing the geometric aspects of real word object, and the latter refers to interfusing the computer-generated content and real world scenery to improve the efficiency and flexibility of VR modelling. During actual modelling, there are three guiding factors for determining which model data type and modelling method to employ—complexity of objects in the real world, the users' intended modality, and the expected degree of model fidelity. Often multiple modelling methods and model data acquisition techniques are combined to generate model data to satisfy the required model fidelity.

MR applications provide a blend of current and historical (theorised) views of CH, as demonstrated by Magnenat-Thalmann and Papagiannakis [2005], Oliva et al. [2015], and Okura et al. [2015]. From a technical point of view, the representation of heritage in an MR environment thus requires two distinct forms of 3D data—current and historical [Addison and Gaiani 2000]. The complementary combination of these forms is referred to as "real-virtual".

3.3 Devices

In general, the main devices required for augmented, virtual, and mixed reality systems are displays, computers, and tracking, camera, and input devices.

3.3.1 *Display.* Presenting virtual content is perhaps the most essential aspect of immersive technologies. Presentation devices are classified according to the kind of virtual content they are designed to display—visual, auditory, or tactile. However, to date, existing CH-related applications, have focused on visual presentation. There are five types of displays. The first, Head-Mounted-Displays (HMD), can be used for AR, VR and MR experiences. The HMDs in AR can either be optical-see-through or video-see-through. Optical-see-though allows users to see part of the real environment through the lenses, while the video-see-through HMD supplies a view from video feeds supplied by multiple wearable cameras. Optical-see-though HMDs have to overlay real space to display the augmented view—users see synthetic content and the real environment coexisting in a virtual space. In the case of video-see-though HMDs, on the other hand, a computing device processes the images coming through the cameras mounted on the HMD, augments the scene with virtual information, and renders the blended images and this approach is therefore more demanding in terms of computation. Since the user sees the real environment through the cameras mounted on the HMD, video-see-through HMDs can trick human perception into believing that virtual and real environments coexist by introducing deliberate delay before rendering the blended image, thereby properly registering virtual information over the real environment [Rolland and Fuchs 2000]. Such control over the registration process is extremely difficult with optical-see-through HMDs, because the user can see the real environment thorough the lenses, firsthand. In any case, the introduced latency must be very low, otherwise users will notice the time gap. HMDs in VR, on the other hand, are not see-through. These displays have been used in a wide spectrum of VR applications to present 3D virtual scenes to users. Such HMDs are connected to a computer for real-time and realistic rendering of virtual scenes. A user's pose is tracked to correct the perspective of displayed images.

The second type of display, Spatial AR (SAR), projects virtual information directly onto the real environment—this approach uses video-projectors, optical features, and tracking devices to achieve the augmentation [Carmigniani et al. 2011]. A recent AR project in the CH domain that use projected displays is the Revealing Flashlight presented by Ridel et al. [2014].

The third type of display, handheld, can be used for AR, VR and MR experiences. It combines a digital camera, inertial and GPS sensors, and a handheld display. These displays, when used for AR and MR experiences, use video-see-through approaches to superimpose virtual content over real environment views. Most AR research in the CH domain focuses on handheld displays [Vlahakis et al. 2001; Kang 2013; Angelopoulou et al. 2011; Casella and Coelho 2013]. Handheld displays are also suitable for non-immersive VR systems. Recent advances in mobile technology, such as Samsung's Gear VR, have made it even more suitable for Immerstive Reality.

The fourth type of display, a desktop screen and projection, is mainly composed of a workbench, projector, and computer. These display systems are common in visualisation environments for non-immersive and semi-immersive VR experiences. With the addition of stereo glasses, desktop displays can provide 3D scene viewing functionality for multiple users. To correct the perspective, tracking methods can be employed to track pose, though tracking is not very often utilized in non-immersive and semi-immersive settings. Gesture-based and device-based interfaces are commonly implemented to allow interaction with the displayed virtual scenes—for instance, the Etruscanning project of Pietroni et al. [2013] uses projector-based display and gesture-based natural interaction to allow users to interact with digital content aimed at experiencing a virtual reconstruction of the Etruscan Regolini Galassi tomb.

The fifth type of display, a Cave Automatic Virtual Environment (CAVE) and related technoligies, is a polyhedral projection display technology that allows multiple users to experience fully-immersive and vivid 3D scenes. Multiple projection displays or screen walls—typically three to six—are conjoined to make up a cave-like cube, in which users are situated to experience enhanced presence in fully-immersive 3D virtual environment. The VR systems presented by Gaitatzes et al. [2001] and Christou et al. [2006] are typical examples of CAVES in CH.

3.3.2 *Computer.* Computing devices are used in AR, VR and MR to run the required software tools. From a hardware perspective, a state-of-the-art system is generally needed to generate and render realistic virtual scenes in real-time. One of the first AR applications, ARCHEOGUIDE [Vlahakis et al. 2001], in the CH domain used laptops with 256 MB RAM that users had to carry when using the application in situ. These days, mobile devices, such as smart phones and tablets, are equipped with much better processing units and memory than high-end laptops from a few years ago. With this rise of mobile device technology, carrying laptops around is now unnecessary.

3.3.3 *Tracking devices and cameras.* Cameras are used for AR and MR applications that depend on marker-based or markerless tracking. Camera and tracking devices are used in combination if a hybrid tracking approach is required. In general, the commonly used tracking devices are electromagnetic, acoustic, and inertial sensors. In the past, camera and tracking sensors had to be attached to laptops. For instance, one of the earliest cultural heritage AR applications presented by Vlahakis et al. [2001], attached a Differential GPS receiver and digital compass to a laptop to provide pose tracking. In contrast, a relatively recent CH application by Kang [2013], exploits the smart-phone's inbuilt inertial sensors and camera to track the pose instead.

3.3.4 *Input devices.* A range of input devices are available. To shift interaction interfaces from desktop-based Graphical User Interfaces (GUI) to more intuitive and natural ones, speech, gaze, and gesture sensors—including wearable devices, such as gloves and wireless wristbands—will substitute for conventional input devices. However, the choice of input device should depend both on the domain of the application, and also the system. For instance, the TOOTEKO AR application presented by D'Agnano et al. [2015] uses Near-Field-Communication (NFC) sensors attached to a 3D printed replica of an artefact as input device, which returns audio content when touched by users. In the case of AR applications that use mobile devices, input and interaction can exploit the touch-screen, microphone and tracking sensors. More generally, the common input devices for interaction and input in VR applications are data gloves, gesture sensors, joysticks, mice, wands, gamepads, and some wearable haptic sensors. For instance, the Etruscanning project, presented by Pietroni et al. [2013], uses a Kinect sensor and Barsanti et al. [2015] use the Leap Motion to allow users to interact with virtual scene through motion sensing.

3.4 Interaction interfaces

Interaction between users and virtual information is one of the essential aspects of immersive reality across domains. Research in the fields of Tangible User Interfaces (TUI), augmented reality and Human Computer Interaction (HCI) aim to provide intuitive and natural interaction interfaces [Kato et al. 2000; Vlahakis et al. 2001; Liarokapis et al. 2005; Billinghurst et al. 2008; Hürst and Van Wezel 2013; Kang 2013].

Interaction also has a defining impact on the sense of presence. Although there is a range of domain-specific definitions, from a VR perspective, presence is the perception of being physically present in a non-physical world. Enhancing a user's presence in a virtual environment, which is an essential experiential aspect of VR, is a cumulative effect of immersion and interaction. The former refers to the sense of being surrounded by a virtual environment, whereas the latter is the possible range of users' interaction with the virtual environment. Therefore, when VR applications become sufficiently immersive and completely embed users within virtual environments, and natural interaction interfaces become a seamless metaphor for interacting with virtual surroundings, a person's perception can be tricked so that they believe themselves to be in a separate, but realistic world. Despite the undeniable fact that immersion has taken the lion's share of VR development, interaction plays a significant role as well.

In general, there are six types of interfaces for augmented, virtual and mixed reality systems: tangible, collaborative, device-based, sensor-based, hybrid, and multimodal interfaces.

3.4.1 *Tangible.* A tangible interface affords interaction that exploits direct manipulation of information through physical objects, and AR's ability to combine computer-generated content and physical environments [Ishii 2008; Shaer and Hornecker 2010]. When its full potential is realised, tangible AR interfaces can support direct augmentation of tangible interfaces. Thus, the same physical object becomes both display and interaction metaphor. Here, it is important to distinguish between using a physical object to interact with virtual information displayed separately elsewhere, and augmenting the physical objects with virtual information and interacting with the augmented view through the same object, which fully integrates TUI and AR. In the narrower sense, applications that use physical input devices and mobile AR applications could be considered tangible AR. The use of touch screens make this interface common in the CH domain. However, the broader case where physical objects are augmented and used as interaction metaphors is not a common approach in the CH domain as it requires physical contact with the artefacts in order to interact with virtual information, which is often not possible due to the fragility and size of the artefacts. However, there are some studies that do investigate this: for instance, the TOOTEKO AR application presented by D'Agnano et al. [2015] uses a tactile 3D printed object as a replica of an actual artefact. The replica is augmented with audio content and users can touch different parts of the tactile surface and get varying audio feedback.

3.4.2 *Collaborative.* Collaborative interfaces make use of multiple displays such as see-through HMD and SAR to support remote, face-to-face, and shared activities [Carmigniani et al. 2011]. When used for face-to-face collaboration, such interfaces rely on tabletop settings to project virtual information, or on see-through HMDs. In both cases, users should be able to see the virtual information from their own perspective. On the other hand, when this interface is employed for remote collaboration, participants can wear a see-through HMD and remotely collaborate in a common virtual space. Reitmayr and Schmalstieg [2004] present such a collaborative AR application using a see-through HMD. Their system is used for collaborative navigation and information browsing at historical sites in an urban environment, thereby providing multiple features so that users can follow, guide and meet other users based on proximity.

3.4.3 *Device-based.* Any interaction interface that uses GUIs, haptic interfaces, and conventional devices, such as mouse, gamepad, joystick, wand, etc., to allow users to interact with the virtual environment, is defined as a device-based interface. Arguably, sensors are a kind of device, but it is important to distinguish between devices and sensors on the basis of their characteristic of demanding touch-based manipulation. The former requires users to physically manipulate the device to function, whereas the latter senses users' natural interactions, such as gesture, speech, and gaze, without physical contact. For example, the interface for "Reviving the past" Gaitatzes et al. [2001], uses a hand-held navigation tool called Wanda^{TM}, which is a tracked device that resembles a traditional three-button mouse but with additional features of a joystick and spatial position tracking.

3.4.4 *Sensor-based.* In general, sensor-based interfaces employ sensing devices to understand natural interaction modes. The flow of interaction commands is not explicitly forwarded from user to system; rather, the system actively perceives the users' intention through sensors. Common sensors include motion tracking, gaze tracking, and speech recognition. The Etruscanning project [Pietroni et al. 2013], and a VR system which presents the "path of the dead", an important ritual in ancient Egypt [Barsanti et al. 2015], use sensor-based interfaces. The former uses the Kinect sensor to sense simple gestures such as turning one's hands right and left and spreading the arms. Whereas the latter uses the Leap Motion sensor to allow users to interact with the displayed virtual scenes through simple hand movements such as grabbing.

3.4.5 *Hybrid.* A hybrid interface integrates a variety of different, but complementary interfaces, and a range of interaction devices [Zhou et al. 2008]. Such interfaces should automatically accommodate a changing set of devices and the interaction techniques associated with them [Zhou et al. 2008]. As a result, users can specify new modes and operations at run time.

When used by AR applications, hybrid interfaces provide the possibility of collaboration among multiple users in the same way as collaborative interfaces. For instance, Benko et al. [2004] present a collaborative mixed reality system integrating a tracked handheld display, see-through HMDs, and multi-touch and multi-user projected displays for archaeological excavation, where users employ a tracked glove, speech commands, and a multi-touch sensitive surface to interact multimodally with the system and collaborate to navigate, search, and view data. The basic difference between collaborative and hybrid interfaces is their purpose and the variety of devices and methods supported: hybrid interfaces may be single user, where by definition collaborative interfaces cannot be.

Inevitably, the hybrid interface is the most commonly used one in CH related VR systems, because it unites the benefits of sensor-based and device-based mechanisms. Accordingly, a combination of sensors and input devices is used to communicate a user's interaction commands to the VR system. In a hybrid interface, sensors are used to track the user's pose for rendering user-centred perspectives, while input devices, typically, are used to interact with the displayed virtual content. The VR application presented by Hernández et al. [2007] uses a hybrid interface combining a wireless pointing device, and inertial and acoustic tracking sensors. The tracking sensors are used for two tasks—to determine user's pose and to allow users to interact with the displayed virtual environment by physically walking in the digital space.

3.4.6 *Multimodal.* A multimodal interface is a fusion of two or more natural interaction modes. Thus, multimodal interfaces use a combination of sensing devices to perceive humans' natural interaction modalities. It is worth distinguishing between multimodal VR experiences and multimodal interfaces. A multimodal VR experience refers to the realism of virtual reality in terms of presence as a result of the effects of the virtual environment on the visual, auditory, and touch senses. Though a multimodal VR experience is implicit in a multimodal interface, the latter refers explicitly to the use of multiple sensors to perceive the commonly used natural interaction modes, such as speech, gaze, and gesture. It is easier to find literatures on multimodal VR than on multimodal interfaces. However, as the technology advances, multimodal interfaces will likely appear in a wider range of domains.

3.5 Systems

Based on intended flexibility, Carmigniani et al. [2011] categorises AR systems into five types: fixed indoor, fixed outdoor, mobile indoor, mobile outdoor, and mobile indoor/outdoor. However, considering AR applications in the CH domain over the past decade, a simpler categorisation into indoor and outdoor AR is warranted. Virtual reality systems, on the other hand, can be classified, based on the intended experience, into non-immersive, semi-immersive, and fully-immersive. These systems are implemented by combining various tracking methods, input devices, displays, and interfaces.

3.5.1 *Indoor AR.* Indoor AR makes use of either marker-based or markerless tracking, see-through HMDs, spatial or handheld displays, and tangible, collaborative, hybrid or multimodal interfaces. Indoor systems do not need GPS, but, if the display is an HMD, the system might use inertial sensors to track the user's viewpoint. For instance, Kim et al. [2009] employ markerless tracking for an indoor tour system, and Choudary et al. [2009], use visual tracking and a handheld display to enhance CH discovery. AR studies, in the cultural computing domain, that employ indoor systems, include [Kim et al. 2009; Choudary et al. 2009; Seo et al. 2010; Ridel et al. 2014; Bostanci et al. 2015].

3.5.2 *Outdoor AR.* Outdoor AR relies heavily on markerless and hybrid tracking, handheld displays, and tangible interfaces. Optical-see-through HMDs and collaborative interface are used in some cases. AR studies, in the cultural computing domain, that use such systems include [Vlahakis et al. 2001; Reitmayr and Schmalstieg 2004; Zoellner et al. 2009a; Seo et al. 2010; Angelopoulou et al. 2011; Mohammed-Amin et al. 2012; Kang 2013; Han et al. 2013; Caggianese et al. 2014; D'Agnano et al. 2015].

3.5.3 *Non-immersive VR.* Non-immersive systems, as the name suggests, are the least immersive versions of VR experience. Such systems do not need a pose tracking method at all. The virtual environment is viewed through a desktop or handheld display. Interaction with the virtual environment can occur via device-based interfaces. A sense of presence in such virtual environments is not expected. Zara [2004] uses such a system for a web-based visualisation of CH.

3.5.4 *Semi-immersive VR.* Semi-immersive VR systems are more akin to a flight simulator. They often consist of a large, concave screen, projection system and monitor, and are more similar to a large screen movie experiences. Semi-immersive systems are a common system in museums, because they can accommodate large number of users simultaneously. Tracking is not required if the experience is intended for multiple users. However, if a single person is using the system, tracking the user's pose might be useful to correct the perspective of the displayed virtual images. The Etruscanning project presented by Pietroni et al. [2013] is a typical example of a semi-immersive VR system implemented in the CH domain.

3.5.5 *Fully-immersive VR.* Telepresence, which is a state of being fully immersed in a virtual environment, is the ultimate effect of immersion and interaction and VR systems that support this are called fully-immersive. Immersing users inside a virtual environment is achieved by displaying a virtual scene from the user's perspective on HMDs and CAVEs. The ability to see one's surrounding physical environment is one of the aspects that differentiates AR from VR. However, this issue also comes into play with fully-immersive VR systems depending on the display device—in the case of HMD-based VR experiences, one cannot see one's body, whereas a CAVE-based experience allows seeing one's body and even others situated in the CAVE. Natural interaction and being situated inside a virtual environment are the essential aspects of telepresence and both HMD-based and CAVE-based VR systems are viable approaches. Interaction during a fully-immersive VR experience is best achieved by employing hybrid and multimodal interfaces as device-based interfaces may break user's immersion, because users will have to focus to some extent on the interaction devices. Fully-immersive VR experiences that have been observed in CH domains include those presented by Gaitatzes et al. [2001]; Christou et al. [2006] and Barsanti et al. [2015].

3.6 Commercial and open source development tools

There have been a number of software frameworks created speicfically to support immersive reality development and this section provides an overview of those more suited to the CH domain. The first discriminant is the choice of the Operating System (OS). This is not trivial, since not all the available frameworks are suitable for the most widely adopted Operating Systems (Android and iOS) and to reach the majority of users, the platform has to be taken into account. There are certain points of overlap between AR and VR, since some existing development platforms are suitable for both experiences.

3.6.1 *AR development toolkits.* The number of development tools is increasing almost daily [1], and this review serves only as a snapshot of the most commonly-used current frameworks, of which Wikitude [2], Layar[3] and Vuforia[4] are commercial, and PanicAR[5], DroidAR[6] and ARToolkit[7] are free. Wikitude is a commercial framework released in 2008 that exploits both *location-based* and *vision-based* tracking. For a description of its use in a museum environment see Caggianese et al. [2014].

Layar is the most widely-used solution for *location-based* services. Being able to store POIs in a remote database (DB) and retrieve associated information based on user location make this framework particularly appropriate for outdoor way-finding experiences [Haugstvedt and Krogstie 2012a].

After the removal of Metaio from the market, which for years was the most powerful tool for developing *vision-based* AR applications, Vuforia has become the toolkit of choice for the vast majority of developers. Empler et al. [2013] present a framework for the visualization of 3D artefacts with Vuforia in archaeological contexts. Its integration with Unity3D enables well-rendered 3D models, and rapid and easy cross-platform development. It supports a variety of 2D and 3D target types, including Image Targets, 3D Multi-Target configurations, and a form of addressable Fiduciary Marker known as a Frame Marker. Additional features of the SDK include localized Occlusion Detection using "Virtual Buttons", runtime image target selection, and the ability to create and reconfigure target sets programmatically at runtime.

Moving on to free or opensource solutions, ARToolKit is a *vision-based* AR library that includes features such as: camera position/orientation tracking, easy camera calibration code, and cross-platform development. Distributed with complete source code, it was initially designed to run on personal computers, making the use of this SDK for the mobile development not preferable [Choudary et al. 2009].

PanicAR, distributed with a free licence, is specifically designed for iOS development and is based on sensor tracking. Kounavis et al. [2012] show its use for *location-based* AR to enhance the tourism experience in an outdoor scenario.

Finally, DroidAR was designed to create AR applications for Android OS with both location- and vision-based approaches. Again the source code is freely available. A test of this tool appears in the work of Quattrini et al. [2016]. From our own tests, Vuforia provides the most reliable tracking in terms of rapidity and stability. In contrast, for outdoor scenarios Layar, unfortunately, has some weaknesses, especially in terms of accuracy. Table I shows the features and weaknesses of the listed tools.

3.6.2 *VR development toolkits.* With the mass market sale of simple VR devices (e.g., Google Cardboard, Gear VR, HTC Vive) accompanied by supporting applications, VR has become more publicly accessible and affordable. Game Engines have become the de facto approach for implementing VR systems, due to the range of support they offer, including management of complex 3D models, interoperability of file formats, rendering, animation, and interaction. Unfortunately, they have the drawback of being complex and represent a significant hurdle for inexperienced programmers.

[1] http://socialcompare.com/en/comparison/augmented-reality-sdks
[2] http://www.wikitude.com
[3] https://www.layar.com
[4] https://www.vuforia.com
[5] http://www.panicar.dopanic.com
[6] https://bitstars.github.io/droidar/
[7] https://artoolkit.org

Table I. : A comparison between the most commonly-adopted AR frameworks in the field of CH.

SDK	**Purpose**	**Tracking**	**Platforms**	**Graphics**	**Cloud, Computing**	**Tracking Sensors**	**License**
Wikitude	Indoor, Outdoor	Inertial, Markerless, Model based	iOS, Android	3DUnity support, 2D images, text, 3D Models (proprietary format)	yes	Camera, GPS, IMU	free and commercial
Layar	Mainly for Outdoor	Inertial	iOS, Android	2D images 3D models (proprietary format)	yes	GPS, IMU	commercial
Vuforia	Indoor	Markerless Model based	iOS, Android	3DUnity, OpenGL 3D models	yes	Camera	free and commercial
PanicAR	Only outdoor	Inertial	iOS	2DImaged Labels	no	GPS, IMU	for free
DroiAR	Only outdoor	Inertial	Android	2D Images Labels	no	GPS, IMU	free
ARToolKit	2Dimages, Markers	Marker Markerless	iOS, Android	3DUnity, Android	no	Camera	GPL

The most popular game engines for VR are Unity 3D[8], OpenSceneGraph[9], Unreal Engine 4[10] and CryENGINE[11]. Unity 3D is perhaps the most developer-friendly platform and is the sole one that allows fully cross-platform development. The most commonly cited drawback is that it does not allow real-time modelling. Bruno et al. [2010] demonstrate its use in the DCH domain.

OpenSceneGraph is widely used for VR, scientific visualization, visual simulation, modelling, games, and mobile applications [Baglivo et al. 2013]. Although, as a high performance 3D graphics toolkit, it is more oriented towards desktop and web-based rather than mobile applications.

Unreal Engine 4 includes outstanding graphical features, and it is probably the best tool for achieving realistic results. Enables one to deploy projects to Windows PC, PlayStation 4, Xbox One, Mac OS X, iOS, Android, VR (including but not limited to SteamVR/HTC Vive, Oculus Rift, PlayStation VR, Google VR/Daydream, OSVR and Samsung Gear VR), Linux, SteamOS, and HTML5. Unreal Editor can run on Windows, OS X and Linux..

CryENGINE is also worth mentioning, even though it is not widely used and requires expert developers. Table II summarizes the main features of these game engines. A more detailed cross comparison of these tools for the CH domain is provided by Herrmann and Pastorelli [2014].

3.7 Summary

Regardless of the domain, the essential aspects and enabling technologies of immersive reality applications are: tracking and registration methods; virtual environment modelling; computer, display, input, and tracking devices; interaction interfaces; and systems.

AR applications in the CH domain frequently use marker-based, markerless, and hybrid tracking approaches. Optical-see-through HMD, handheld, and spatial/projected displays are the common choices for displaying augmented views, whereas tangible and collaborative interfaces are used more often to interact with virtual information, though alternatives do exist. AR systems in CH are more com-

[8]https://https://unity3d.com
[9]http://www.openscenegraph.org
[10]https://www.unrealengine.com
[11]https://www.cryengine.com

Table II. : A comparison between the most commonly adopted VR game engines in the field of CH.

SDK	License	Dev.Platform	Mobile Platform	Visual Editor	VR Target
Unity 3D	Proprietary	Windows, OSX, eucalyptus	Windows Phone, iOS, Android, Tizen	Yes	Oculus Rift, Gear VR
OpenSceneGraph	Open Source	Linux, Windows	-	No	-
Unreal	free and commercial	Windows, Mac OS X, Linux	iOS, Android	Yes	HTC Vive, Oculus Rift, Google VR, Samsung Gear VR
CryENGINE	free and commercial	Windows, Mac OS X, Linux	iOS; Android	Yes	PlayStation, XBox, HTC Vive, Oculus Rift, Google VR, Samsung Gear VR

monly outdoor than indoor. Recent advances in computer technology, however, provide the necessary enabling technologies for a combination of indoor and outdoor use. For instance, HoloLens is an optical-see-through HMD and a holographic computer, which allows users to interact with virtual content via gaze, gesture, and speech [Microsoft 2016]. This device is untethered and equipped with a depth camera, inertial sensor, optical-see-through display, optical tracking, and Holographic Processing Unit, thereby making it viable for AR applications intended for both indoor and outdoor environments with tangible, collaborative, hybrid, and multimodal interfaces.

VR applications in the CH domain use electromagnetic, inertial, acoustic, IR and hybrid tracking approaches with IR and inertial tracking most frequent. HMD, desktop, and CAVE displays are the common choices for displaying the virtual environment. Device-based, sensor-based, and hybrid interfaces are used most often to interact with the virtual environment, though multimodal interfaces are more intuitive and natural. The most common VR systems employed in cultural heritage are semi-immersive and fully-immersive. Recent advances in HMD, tracking sensors and computer graphics technologies enable very realistic modelling and real-time rendering of virtual environments, but this has yet to be widely adopted in CH.

4. CULTURAL HERITAGE APPLICATIONS

On the whole, cultural heritage sites and artefacts gain significant added value from enrichment through digital media. Nevertheless, many art curators believe that the use of technology relegates art to the background [Cameron and Kenderdine 2007]. This attitude seems to stem from either a cultural or generational source. First, there is widespread scepticism among those not comfortable with technology about the benefits of mobile technologies. Second, and more importantly, there are issues with the way technology is used. The trend in multimedia applications is towards the show and glamour of innovation, rather than a focus on solving specific problems with digital [Pierdicca et al. 2016a].

However, there is general agreement that visual CH tools suitable for users unskilled in multimedia technologies are important for CH dissemination [Cignoni and Scopigno 2008]. This is particularly the case for younger participants. Generally, museum installations that do not introduce new technologies, are rightly or wrongly regarded as less interesting and attract fewer visitors [Gerval and Le Ru 2015]. Learning experiences in museums that rely only on labels and descriptions may be informative but they are not interactive [Lu et al. 2014]. The creation of an intelligent environment that is responsive to human presence, adapts dynamically and supports mobile technology makes the visit path more appealing, opening up new avenues in the CH domain [Manovich 2006].

Immersive reality systems have proven to be a viable solution in this regard, allowing navigation, interaction and discovery in different settings and with a variety of purposes. In archaeology, for example, the problem of the dissemination of heritage is often related to communicating goods that are either seriously damaged or definitively lost. Technologies can serve an X-Ray-like function to show what is concealed under the ground, or to augment an environment with virtual reconstructions of lost heritage [Clini et al. 2016].

From these considerations arises the need for a classification of Cultural Heritage application areas, in order to better understand where AR, VR and MR can offer successfull solutions. Accordingly, we classify the purpose of immersive reality in CH as: education, exhibition enhancement, exploration, reconstruction, and virtual museums.

—Education aims at enabling users to learn the historical aspects of tangible and intangible CH.
—Exhibition enhancement is intended to improve the visitor experience at physical museums and heritage sites, typically through tour guidance.
—Exploration supports users in visualizing and exploring historical and current views of CHs to discover, interpret, and acquire new insight and knowledge.
—Reconstruction aims at enabling users to visualise and interact with reconstructed historical views of tangible and intangible CHs. Two characteristics differentiate this from exploration: it does not solely target experts and the visualisation and interaction do not necessarily extend to discovery of new insights.
—Virtual museums simulate and present tangible and intangible CHs in digital museum form to the public.

Considering the objective of these application areas, we next discuss technological suitability and technical requirements. Figure 4 summarises these requirements in tabular form.

(1) *Education*. In some senses every research area that deals with the dissemination and diffusion of CH must consider education. However, our focus here is on tools and applications where learning is the primary aim [Bacca et al. 2014]. As an example, museum designers have recently turned to leveraging immersive realities' capacity for spatial and temporal representation, narrative and interactivity, real-time personalized scaffolds, and collaboration, to create meaningful learning experiences in medicine and human biology [Matuk 2016]. By enhancing a sense of place, for instance by improving the visit or way-finding in a virtual environment, the learning activity can be significantly improved [Chang et al. 2015]. Gargalakos et al. [2011] discuss how playful learning can cross boundaries between schools, museums and science centers, by involving participants in extended episodes of digital interaction with the exhibition. This approach provides significantly improved learning outcomes, increasing students' curiosity, their willingness to share their experiences, their eagerness to use new technologies, and acquire knowledge. In a similar vein, the work by Invitto et al. [2014] considers various interventions and studies related to new technologies and new scientific languages, based on the learning objective. The idea is to enhance the usability of the MAUS Museum through an AR application and Virtual Reality projections, related to the natural sciences (Plankton 3D and Tarbosaurus 3D). There is thus evidence that educating users on the historical aspects of both tangible and intangible CHs requires presenting the content in an entertaining environment. To this end, the system should be immersive and interactive. Tangible educational CH needs users' active interaction with the displayed content. An interface in such cases must be as natural and intuitive as possible. Users' inexperience with such applications

should not be a constraint that prevents delivering the historical aspects as intended. A user's age, background, and knowledge of the domain may differ, and the system should adapt accordingly. Intangible CHs, however, do not need to rely on adaptive interfaces to the same extent, because ready-made audio-visual content is presented, and user interaction is often limited to playing and pausing the content. For tangible CH, HMDs and CAVEs with a high-resolution display and realistic rendering capability can achieve the required immersion. Tracking is mandatory to enhance the immersion and interaction. A combination of inertial and IR sensors can provide the user's pose. Interface-related tracking is better achieved by natural interaction such as gesture, gaze, and speech sensors. Tracking is not required if intangible CHs are presented, but it can enhance the experience. Both VR and MR can be used to achieve educational support in a fully-immersive environment. AR may not be a suitable alternative as it overlays virtual and real-world views, while the focus of educational applications tends to be historical.

(2) *Exhibition enhancement*. Enhancing a visitor's experience can take place indoors or outdoors, or sometimes both, based on the location of CH assets. In all cases, a virtual element such as a description, guide map, virtual-human character, is superimposed over the users' current view of the real world. The number, and the quality, of applied research papers in this field is high, since AR can provide a variety of solutions to help museums fulfill their role and goals [Choi 2014] Regardless of the type of installation there is evidence that visitor interest grows when such immersive solutions are adopted [Chang et al. 2014]. In the user study conducted during the ARCO project [Sylaiou et al. 2010] this same trend was evident. In fact, in many cases an immersive reality approach enables new media and storytelling, that represents the major highlight of a user's experience [Pescarin et al. 2012]. The work of Liestøl [2014] in uncovering the Appian way and [Ozden et al. 2014] on user interaction modules for two Istanbul museums are good examples. In another case [Petridis et al. 2013], the user experience was made more immersive, engaging, and interactive at the Herbert Museum and Art Gallery. In Sdegno et al. [2015], painted architecture by Paolo Veronese was brought to life thanks to a 3D reconstruction, while in Pierdicca et al. [2015b] and Clini et al. [2014] the famous painting "La Città Ideale" was augmented with digital information without requiring artificial markers. The use of mobile devices is increasing in the cultural and museum sectors, as are the number of apps (e.g. on Google Play and the Apple Store) and many Museums' Apps are good examples of technological integration with experience design.
In general, both AR and MR can be employed for exhibition enhancement. VR cannot be used since it blocks the real word views. See-though HMDs, however, can deliver immersive experiences of both indoor and outdoor sites, but the virtual elements should not distract visitors' view of the real world, because the aim is enhancing a visit experience at physical museums and CH sites, not substituting it with virtual views. Therefore, the rendering should be vivid and realistic, the tracking must be robust, and the registration must be fast, especially, if optical-see-through HMDs are used. Otherwise, a user's experience will be unpleasant. In the case of indoor systems, a combination of markerless and sensor-based tracking methods can be employed. Marker-based and other approaches that need physical attachment to a CH asset should be avoided, because such practices damage the historical value of CH assets. Regarding outdoor systems, a combination of Differential GPS, sensor-based, and markerless methods can be used to achieve tracking. If users can approach the CH asset, then a markerless method is a suitable choice, otherwise, long-range optical sensors and Differential GPS are more appropriate. Most of the time, visitors tend to attend museums and CH sites in groups. Hence, the interaction interface should be collaborative and intuitive so that users can experience the visit from their own perspective and at the same time collaborate with co-located visitors. This can be extended to accommodate remote collaboration between spatially distributed visitors.

(3) *Exploration*. Exploration-based applications primarily focus on the historical and current aspects of tangible archaeological CHs, especially, to allow users to discover, explore, visualise, and manipulate the content, thereby leading to knowledge creation and new insights. Users of such applications are assumed to have expertise in the domain, therefore, the system can assume prior knowledge of domain-specific visualisation. Exploration-focused applications need hybrid tracking, a combination of complementary displays, collaborative and multimodal interfaces, and distributed and immersive environments. As the users are assumed to be experts in the domain, the tracking method can focus on accuracy over user experience, however, this should not be at a cost of compromising users' comfort. To this end, a combination of sensor-based methods can fit the purpose of indoor environments, and Differential GPS and sensor-based methods can achieve outdoor tracking. If the exploration tasks are at distributed locations, the pose readings from all locations must be synchronised, otherwise, users cannot collaborate seamlessly. A suitable combination of displays could consist of HMDs and table-top projectors for indoor, and HMDs for outdoor settings. Table-top projectors and CAVEs can accommodate multiple users at a time, and HMDs can display user-centred perspectives. Interactions with the displayed content rely heavily on the accuracy of interface-related tracking methods. For this, sensor-based input devices and natural interaction mode sensors should be used in combination. MR and AR are the best choices for exploration purposes, because users can see both the real world and virtual views. This feature is especially invaluable in archaeological settings. The possibility of enriching reality with computer generated information, providing innovative information access at CH sites, has been noted in recent research. Verykokou et al. [2014], for instance, visualize a part of the Middle Stoa in the Ancient Agora of Athens (see Figure 2a) and users have the opportunity to see what this building looked like in ancient times, as its three dimensional model is displayed on the camera view of their device, projected on the modern-day ruins. Related examples of AR for exploration can be found in the work of Etxeberria et al. [2012], Pierdicca et al. [2015a], Stanco et al. [2012], Deliyiannis and Papaioannou [2014] and Empler [2015]. From this brief analysis, three main points arise: first, AR applications in this domain are restricted to *sensor-based* AR (see Section 3.1.2), and interaction with virtual archaeological content in museums has not spread. Second, AR is mainly used to visualize lost or posited artefacts. Third, for archaeology the use of geomatics applications is unavoidable [Portalés et al. 2009]. Virtual reconstructions (see Figure 2b), in fact, must rely on accurate data sources [Pierdicca et al. 2016b; Quattrini et al. 2016]. Interaction is key to making such experiences more attractive for users and involving them actively in the exploration process, as shown in the well-designed mobile interaction solutions of Wiley and Schulze [2015] and Kang [2013]. In the last decade, archaeology has benefited from the widespread availability of digital 3D models [Comes et al. 2014], allowing developers to represent difficult to reach environments, for example, in underwater conditions [Haydar et al. 2011]. The challenge, discussed further in Section 5 is twofold: on the one hand, describing a known workflow that moves from data acquisition to the visualization in an immersive environment. On the other hand, making this data portable and suitable for different devices or platforms. Besides, these technologies can better accommodate collaborative and multimodal interaction. VR systems cannot meet these requirements to the same extent. However, if collaboration is not needed, HMD-based VR can suffice.

(4) *Reconstruction*. Applications for reconstruction display reconstructed views of tangible and intangible CHs. Such applications allow users to visualise CH assets that existed only in the past or that partially exist. Reconstructed assets can be presented in three forms: tangible, intangible, and a blend of both. AR and MR are best suited to tangible and a blend of tangible and intangible, because both technologies can superimpose the reconstructed views over their historical location. Additional information beyond the virtual reconstruction itself can also be overlaid [Saggio and

(a) The Ancient Agora of Athens visualized in the real scene

(b) The on-site visualization of the virtual reconstruction Roman Theatre in Fano, Italy

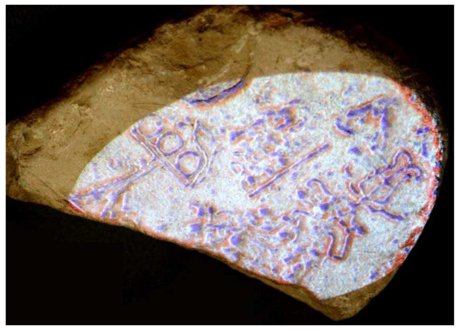
Fig. 2: Examples of AR applications for archaeological purposes. Ancient architecture visualized in its original location thanks to the use of *location-based AR*.

Borra 2011]. To ensure the preservation of artifacts, such as statues or paintings, they must be analyzed to diagnose physical frailties that could result in permanent damage. While such diagnosis is aided by advancements in digital imaging techniques and computer-aided analysis the ability to work directly with the artifact in the field remains limited. Several examples of different kind of diagnosis are reported by Colizzi et al. [2010]. Of particular interest is the work of Girbacia et al. [2013] on a workflow for the restoration of religious heritage, starting from the reconstruction of statues and extending to their in-place geo-located visualization in AR. Vanoni et al. [2012] describe ARtifact, a tablet-based augmented reality system that enables on-site visual analysis (see Figure 3a). Their idea is to use overlaid layers to represent images acquired from different data sources. Another tool (Figure 3b), "the revealing flashlight" [Ridel et al. 2014], is intended to distinguish details obscured by aging effects. This system works by projecting an expressive 3D visualization that highlights features, based on an analysis of previously acquired geometry at multiple scales. The novelty mainly lies in the interaction, which is based on gestures.

VR, on the other hand, is suitable for intangible reconstruction and visualising tangible assets in indoor environments, because this does not rely on displaying reconstructed views over their historical location. In the case of AR and MR, positional tracking can be achieved using a combination of GPS, orientation sensors, and markerless tracking. VR requires tracking to correct perspective and this can be achieved through orientation sensors attached to HMDs or stereo glasses. Users of a reconstruction application may range from domain experts, students, to the general public. Hence, the system should be inclusive of these groups' background. To achieve such inclusiveness, more focus should be given to interaction and presentation aspects. As a result, such applications should have a mutimodal interface and immersive features. In general, see-through HMDs' can fit the requirement for AR and MR systems, and CAVEs will do the same for VR.

(5) *Virtual museums*. In general, virtual museums simulate physical museums and CH sites including their tangible and intangible assets. Much of the time, such assets are inaccessible and fragile. Hence, the simulation must be very realistic and detailed to serve as a replica of artefacts so that users cannot easily discern differences between the originals and their replicas. Such simulations

(a) The ARtifact application, a tablet-based AR tool designed for interactive analysis of cultural artefacts



(b) The Revealing Flashlight is a tool that projects an expressive 3D visualization highlighting artefact features

Fig. 3: Some examples of tools aimed at facilitating restoration, thereby improving analysis. The applications highlight features that are not visible with the naked eyes.

enhance users' presence in virtual museums, thereby tricking users into feeling as if they are physically present at an actual museum or CH site in situ. This can be extended to represent users as virtual-human characters inside the simulated environment so that users who share this environment can see co-located users. To achieve this, the chosen modelling method should blend prerendered scenes and virtual-human characters in real-time. Also, such virtual characters should not be mere avatars but close approximations of the actual users in order to simulate real-life interaction. Hence, the simulation should consider the behavioural and physical properties of users. In addition, the system should be fully-immersive. Users should be able to interact via gesture, gaze, speech, and movement. The enabling sensors for such interfaces should not remind users of their attachment to the real world. Otherwise, presence in the virtual museum will be interrupted. For instance, sensors physically attached to users may require direct manipulation compared to remotely placed sensors, which may result in decreased presence. Also, the interaction should create a perception of physical movement inside a digital environment. In general, HMD-based Augmented Virtuality (AV) and CAVE-based VR environments can achieve a fully-immersive virtual museum. However, large-scale CAVEs are more appropriate, because such environments can accommodate multiple users, and virtual-human characters are unnecessary.

Some of these categories overlap. For instance, a reconstruction application might also allow a user to learn the history of the reconstructed CH. Thus, education and reconstruction purposes coexist under such conditions. Despite such characteristics, the central objective of the surveyed applications generally favour a particular purpose over others. Accordingly, we categorise a number of augmented, virtual and mixed reality applications on the basis of these themes. See Tables III, IV, and V.

The following sections discuss the surveyed papers from the perspectives of enabling technology, system, and purpose as observed in the survey. Moreover, some suggestions are made based on these observations as to which technologies are most suited to a given purpose. These suggestions differ from those discussed above, because those suggestions are made based on the central objective of the identified application areas, whereas the suggestions below are based on the technologies adopted by the surveyed works.

4.1 AR applications

Most AR applications are aimed at exhibition enhancement, followed by reconstruction and exploration. Table IV and Figure 5 show the details of these applications. Hybrid tracking is a relatively common approach, with markerless, sensor-based, and marker-based methods used in that order. In terms of presentation devices, mobile displays make up the majority followed by HMDs, a combination of diverse displays, desktop, custom-built, and SAR displays. In terms of interfaces, most applications use a tangible interface, followed by natural, collaborative, multimodal, and hybrid interfaces. In addition, most of the surveyed applications were targeted at indoor conditions and a few applications for both indoor and outdoor environments.

There are two notable differences in the environmental settings for AR applications.

4.1.1 *Indoor systems.* Most indoor applications focus on exhibition enhancement. The tracking methods used are marker-based and markerless. A significant number of indoor applications use mobile devices for display, and tangible interaction interfaces are the most common.

4.1.2 *Outdoor systems.* The majority of outdoor applications are aimed at reconstruction. Hybrid tracking is often adopted. In terms of display and interface, mobile devices and tangible interface are common choices, respectively.

In general, indoor applications are more suited to exhibition enhancement experiences since physical museums tend to use such applications for virtual tour guidance more often than outdoor CHs. Outdoor applications are more suitable for a reconstruction approach, because it is then possible to overlay reconstructed historical views over the real world. Moreover, a reconstruction theme is often applied to outdoor sites that have been demolished or worn away.

4.2 VR applications

In our findings, the majority of VR applications serve virtual museums, followed by education, reconstruction, and exploration purposes, in that order. Table V and Figure 6 show the details of these applications. Most do not use any tracking methods at all. This is because these applications are non-immersive or semi-immersive. The remaining applications use hybrid, electromagnetic, and optical tracking methods. In terms of presentation devices, a screen/projector is used by the majority of the applications followed by CAVE and HMD. In terms of interfaces, most of the applications use a device-based interface followed by sensor-based, multimodal, and hybrid interfaces. Applications tend to be semi-immersive.

We discuss these applications from the perspective of their level of immersion because their systems range across non-immersive, semi-immersive, and fully-immersive environments.

4.2.1 *Non-immersive.* The areas of non-immersive applications are education, virtual museums, and reconstruction. These applications do not use any tracking methods. They employ desktop screens for displaying the virtual content, and use device-based interfaces. Therefore, desktop screen and device-based interfaces seem to be sufficient for non-immersive experiences for education, virtual museum, and education themes. Pose tracking is not required for non-immersive systems.

4.2.2 *Semi-immersive.* Virtual museums and education are the areas of the majority of the semi-immersive applications. However, a few applications serve reconstruction and exploration purposes. Electromagnetic, optical, and hybrid methods are used to track the pose of users and interaction devices in a few applications, but most applications do not use any tracking. This is acceptable given that users see pre-rendered virtual content and most often tracking is only required for interaction. Moreover, tracking may be unnecessary if a gamepad or mouse is used. In terms of presentation devices, back-projected screens and 3D stereo displays are common choices for semi-immersive applications. Most applications use device-based interfaces, with a few using sensor-based and hybrid interfaces. Hence, optical, electromagnetic, and hybrid tracking methods, back-projected screens and 3D stereo displays, and device-based, sensor-based, and hybrid interfaces are viable for semi-immersive systems intended for virtual museums, reconstruction, education, and exploration.

4.2.3 *Fully-immersive.* A virtual museum is the most frequent application area for fully-immersive VR. A few applications achieve eduction and exploration themes, though. Most applications use hybrid tracking with a few systems employing electromagnetic and optical methods. Fully-immersive experiences are achieved by CAVE and HMD displays. Device-based interfaces are widely adopted. However, a few applications use multimodal and sensor-based interfaces. Therefore, fully-immersive VR experiences to support virtual museums, education, and exploration are best achieved by adopting electromagnetic, optical, and hybrid tracking methods, CAVE and HMD displays, and device-based, sensor-based, and multimodal interfaces.

4.3 MR applications

The majority of the surveyed MR applications exhibit a reconstruction purpose followed in order by education, exploration, and virtual museums. Table III and Figure 7 show the details of these applications. Most of these applications are designed for non-immersive experiences. Hybrid tracking, often a fusion of GPS and markerless, GPS and IMU, and inertial, electromagnetic, and acoustic tracking methods are used. Mobile displays are commonly used to present visual and audio content. However, some systems also use custom-built HMDs, and combinations of different types of presentation devices to display real-virtual content.

MR applications in the CH domain are not as widespread as AR and VR. This is understandable given that the technological aspects of MR are still in their infancy. However, when robust real-time tracking, 3D registration, realistic virtual environments, natural interfaces, and presentation devices for vivid experiences reach fruition, more MR applications will likely appear in the CH domain. Considering the current systems in the domain, however, hybrid tracking, HMD and mobile display, and tangible interface seem to satisfy the needs for implementing MR in the CH domain, especially when focusing on reconstruction.

5. DISCUSSION: CURRENT ISSUES AND FUTURE DIRECTIONS

This survey provides an exploration of research and examples of the different way in which cultural artefacts can be experienced in an immersive form through the application of AR, MR and VR technology. The taxonomy provided in section 4 demonstrates that these technologies are suited in a wide variety of sub-domains. What emerges in the main is the need for curators to provide users with a new perspective on their collections. Museums for example, can increase their appeal by augmenting their artifacts or paintings with digital media, archaeological areas can bring to life lost architectures or ruins. However, there are still many hurdles preventing the acceptance and difussion of immersive technologies in Cultural Heritage. These hurdles are mainly due to: i) technological limitations, ii) content complexity and iii) human factors. First, there are many aspects of immersive technology, such as sensor-based tracking, that could benefit from further attention. Second, the model resolution requirements of CH often exceed the capacity of current technology, particularly with respect to internet retrieval. Third, without careful consideration of human factors as they affect the user experience, immersive technologies are unlikely to experience widespread adoption.

Considering the ongoing research on tracking and registration, realistic rendering, HCI, and CH, we expect further research in the following areas:

(1) *Robust Tracking*. *Sensor-based* tracking using commercial devices, particularly in an outdoor CH environment, remains error prone and has necessitated hybrid solutions. However, the situation is likely to improve with recent investment in these technologies. In this respect, *Camera-based* approaches are a more mature technology in terms of accuracy and reliability, but there is still no prevailing standard.
(2) *Standardisation*. Despite its advantages, immersive reality has not been widely adopted by art curators and managers. Partly this can be traced to a lack of standardization, which could facilitate rapid, sequential development projects. In AR the only available standard is the ARML 2.0 (Augmented Reality Markup Language), provided by Open Geospatial Consortium (OGS), which is primarily oriented towards location-based services. Proposed alternatives include a service-oriented strategy [Rattanarungrot et al. 2014] or standardization of the entire AR architecture [Sambinelli and Arias 2015]. The community could also benefit from a self-documenting standard data format that describes the structure as well as data types and meanings of values for text, 3D models, images, audio and video. VR systems also lack effective formal or de facto standards. Fragmentation of descriptive, structural and administrative metadata for 3D media causes interoperability issues that hamper the exploitation of 3D models on different platforms. However, in VR the most widespread standard is X3D, a royalty-free ISO standard XML-based file format for representing 3D computer graphics. The adoption of a common representation for scanned models would represent a turning point for researchers dealing to the acquisition and reconstruction of ancient artefacts [Fernández-Palacios et al. 2017]. Visualization issues are mainly entrusted to the worldwide adoption of WebGL, which offers the ability to render 3D scenes within any common browser.
(3) *User-driven Semantics*. To deal with clutter in information rich environments, allow users to focus on particular points of interest, and adapt the cultural heritage experience to their preferences, one approach is to exploit semantic web technologies, such as OWL, RDF, and SPARQL. While this approach is not novel in iteself [Hatala and Wakkary 2005; Van Aart et al. 2010; Matuszka 2015; Kovachev et al. 2014; Damala and Stojanovic 2012], it does open up possibilities for citizen participation [Ruta et al. 2014].
(4) *Tangible AR*. A number of augmented reality applications use tangible interfaces in a much narrower scope than its potential warrants. We hope to see more research that integrates Tangible User Interfaces and augmented reality so that future applications, irrespective of domain, will be able to augment physical objects with virtual content and enable interaction with this content through the augmented objects.
(5) *Fully-immersive VR*. Fully-immersive VR systems are not common for a number of reasons. The expense of CAVE technology being one. Recent advances, however, provide relatively affordable technologies such as the Oculus Rift, Microsoft HoloLens, and the HTC Vive, which are HMDs capable of high-resolution rendering, pose tracking, and natural interaction with virtual content. Thus, fully-immersive VR applications will likely appear soon in a wider range of domains. We hope the CH domain will make use of such technologies to realise virtual museums, reconstruction, exploration, and education in a fully-immersive virtual environment.
(6) *Multimodal interfaces*. A multimodal interface is a very intuitive interface and AR, VR and MR systems can exploit this potential. However, it is extremely difficult to implement such interfaces with the state-of-the-art in HCI. However, as research in sensor technology, speech recognition, and artificial intelligence advance, multimodal interfaces will likely become more prevalent in CH and other domains, thereby allowing users to interact with virtual content through all their senses.

6. CONCLUSION

In this paper we have surveyed augmented, virtual and mixed reality from a cultural heritage perspective focusing on aspects such as tracking and registration, virtual environment modelling, presentation, tracking, and input devices, interaction interfaces, and systems. Moreover, we have categorised a number of CH-related augmented, virtual, and mixed reality applications into the general application areas of education, exhibition enhancement, exploration, reconstruction, and virtual museums. Also, we have discussed the technological requirements to support these areas. Though, the ultimate choice of enabling technology must depend on the experience that an application is intended to provide, we make the following suggestions as to which systems are more viable for a given purpose.

Even though augmented, virtual and mixed reality can all be used to achieve the above-mentioned purposes, our survey shows that augmented reality is preferable for exhibition enhancement. Similarly, virtual reality seems better for virtual museums, and mixed reality most viable for both indoor and outdoor reconstruction applications.

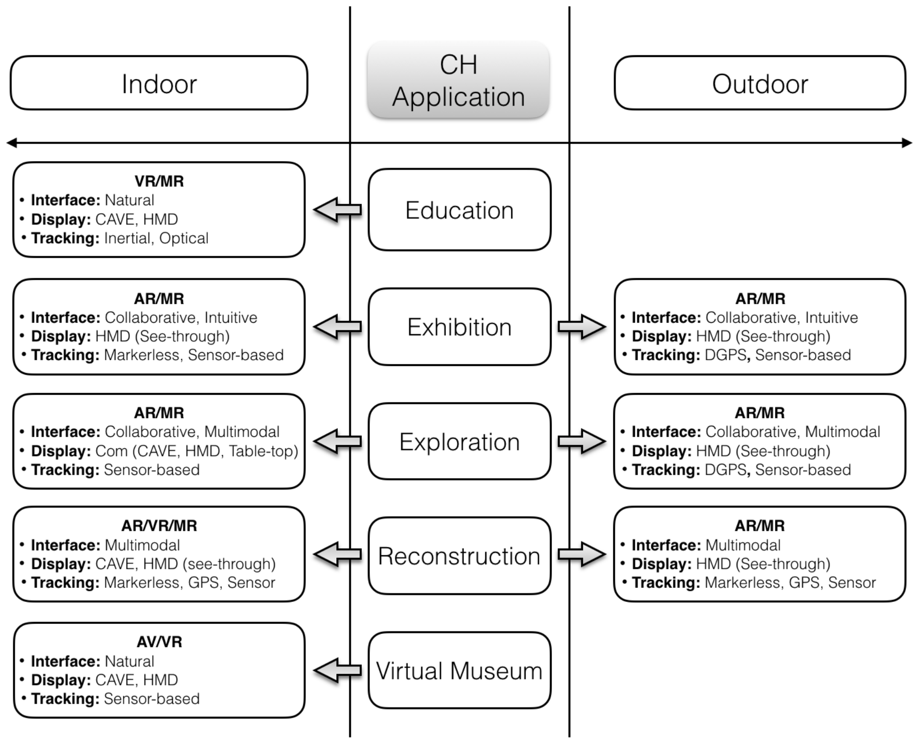


Fig. 4: Considering the identified application areas of CH, the above diagram shows the technical requirements of augmented, virtual, and mixed reality systems in indoor and outdoor settings.

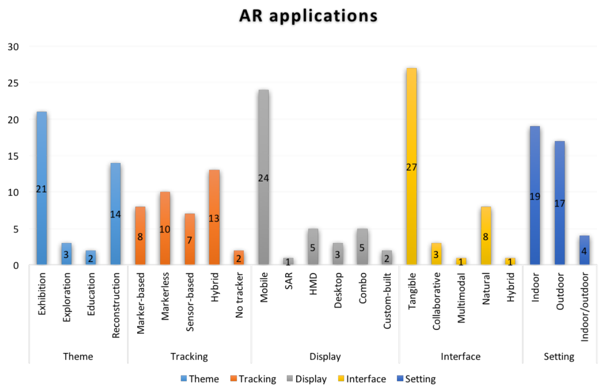


Fig. 5: The purposes and enabling technologies adopted by AR applications in CH

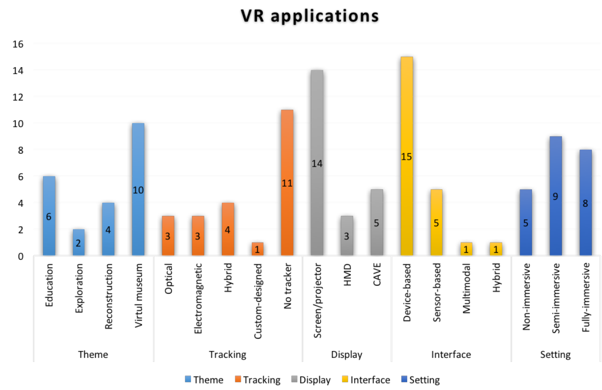


Fig. 6: The purposes and enabling technologies adopted by VR applications in CH

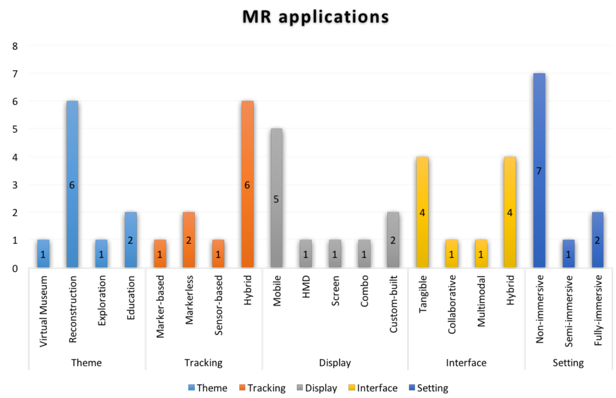


Fig. 7: The purposes and enabling technologies adopted by MR applications in CH

Table III. : The surveyed MR applications in the CH domain and their purpose and the enabling technologies they adopted

Application	Purpose	Tracking	Display	Interface	Setting
Schnädelbach et al. [2002]	Reconstruction	Hybrid (rotation sensors and GPS)	Custom-built (Tripod-mounted display)	Tangible (Device based)	Non-immersive
Magnenat-Thalmann et al. [2004]	Reconstruction	Markerless	Mobile (laptop)	Tangible	Non-immersive
Dow et al. [2005]	Education	Hybrid (GPS and IMU)	Mobile (Audio presentation device and tablet)	Hybrid (Tangible, device-based)	Non-immersive
Liarokapis et al. [2007]	Virtual museum	Hybrid (Marker-based and sensors)	Mobile (laptop)	Multimodal (audio-visual)	Non-immersive
Chrysanthi et al. [2012]	Education	Marker-based	Plasma screen	Tangible	Non-immersive
Durand et al. [2014]	Reconstruction	Sensor-based (IMU)	Mobile	Tangible	Non-immersive
Okura et al. [2015]	Reconstruction	Hybrid (GPS and Markerless)	Mobile	Hybrid (Tangible, device-based)	Non-immersive
Santos et al. [2010]	Reconstruction	Hybrid (markerless, GPS, IMU)	Custom-built (HMD-like)	Collaborative	Semi-immersive
Benko et al. [2004]	Exploration	Hybrid (inertial, electromagnetic and acoustic)	Combo (HMD, projected table, large screen)	Hybrid (Multimodal and collaborative)	Fully-immersive
Magnenat-Thalmann and Papagiannakis [2005]	Reconstruction	Markerless	HMD	Hybrid (Tangible, device-base)	Fully-immersive

Table IV. : The surveyed AR applications in the CH domain and their purpose and the enabling technologies they adopted

Application	Purpose	Tracking	Display	Interface	Setting
Wojciechowski et al. [2004]	Exhibition enhancement	Marker-based	Desktop screen	Hybrid (Tangible and Web-based)	Indoor
Miyashita et al. [2008]	Exhibition enhancement	Hybrid (Markerless and IMU)	Mobile	Tangible	Indoor
Portalés et al. [2009]	Reconstruction	Markerless	HMD	Natural (Movement-based)	Indoor
Choudary et al. [2009]	Exploration	Marker-based	Mobile	Tangible	Indoor
Zoellner et al. [2009b]	Reconstruction	Markerless	Combo (Mobile (UMPC) and MovableScreen)	Tangible	Indoor
Kim et al. [2009]	Exhibition enhancement	Markerless	Laptop	Tangible	Indoor
Haydar et al. [2011]	Reconstruction	Marker-based (optical)	HMD	Tangible	Indoor
Damala et al. [2012]	Exhibition enhancement	No pose tracking, gaze, acoustic, and biosensor	Custom-built (See-through glass)	Natural (Sensor-based interface)	Indoor
Ridel et al. [2014]	Exploration	Hybrid (electromagnetic and optical)	SAR	Tangible	Indoor
D'Agnano et al. [2015]	Exhibition enhancement	No pose tracking (audio-based AR)	Mobile	Tangible (3D print with tactile surface)	Indoor
Damala et al. [2016]	Exhibition enhancement	Hybrid (IMU and markerless)	Mobile	Tangible (iPhone in a loupe-like wooden case)	Indoor
Breuss-Schneeweis [2016]	Exhibition enhancement	Marker-based	Mobile	Tangible	Indoor
Invitto et al. [2014]	Education	Hybrid	Desktop	Natural	Indoor
Chang et al. [2014]	Exhibition enhancement	Markeless	Mobile	Tangible	Indoor
Petridis et al. [2013]	Exhibition enhancement	Marker-based	Mobile	Natural	Indoor
Sdegno et al. [2015]	Exhibition enhancement	Marker-based	Combo	Tangible	Indoor
Pierdicca et al. [2015b]	Exhibition enhancement	Markerless	Combo	Tangible	Indoor
Clini et al. [2014]	Exhibition enhancement	Markerless	Mobile	Tangible	Indoor
Dieck et al. [2016]	Exhibition enhancement	Sensor-based	HMD	Natural (Gaze)	Indoor
Vlahakis et al. [2001]	Exhibition enhancement	Hybrid (GPS and compass)	Combo (Mobile and HMD)	Multimodal	Outdoor
Reitmayr and Schmalstieg [2004]	Exhibition enhancement	Sensor-based (GPS)	HMD	Collaborative	Outdoor
Pierdicca et al. [2015a]	Exploration	Sensor-based (GPS)	Mobile	Tangible	Outdoor
Girbacia et al. [2013]	Reconstruction	Markerless	Mobile	Natural	Outdoor
Fritz et al. [2005]	Exhibition enhancement	Sensor-based (IMU)	Custom-built binocular-like video see-through	Tangible	Outdoor
Zoellner et al. [2009a]	Reconstruction	Markerless	Mobile	Tangible	Outdoor
Haugstvedt and Krogstie [2012b]	Reconstruction	Sensor-based (GPS)	Mobile	Tangible	Outdoor
Chang et al. [2015]	Education	Hybrid	Mobile	Tangible	Outdoor
Han et al. [2013]	Reconstruction	Hybrid (GPS and Markerless)	Mobile	Tangible	Outdoor
Amato et al. [2013]	Exhibition enhancement	Hybrid (GPS, RFID, compass)	Mobile	Tangible	Outdoor
Kang [2013]	Reconstruction	Sensor-based (GPS)	Mobile	Tangible	Outdoor
Empler et al. [2013]	Reconstruction	Markerless	Mobile	Tangible	Outdoor
Caggianese et al. [2014]	Exhibition enhancement	Hybrid (GPS and IMU)	HMD	Natural (Gesture-based)	Outdoor
Pacheco et al. [2015]	Reconstruction	Hybrid (GPS and IMU)	Mobile	Tangible	Outdoor
Huang et al. [2016]	Exhibition enhancement	Hybrid (GPS and IMU)	Combo (Mobile and HMD)	Collaborative	Outdoor
Canciani et al. [2016]	Reconstruction	Markerless	Mobile	Tangible	Outdoor
Petrucco and Agostini [2016]	Reconstruction	Hybrid (GPS and IMU)	Mobile	Tangible	Outdoor
Angelopoulou et al. [2011]	Exhibition enhancement	Marker-based	Mobile	Collaborative	Indoor and outdoor
D'Auria et al. [2015]	Exhibition enhancement	Hybrid (IMU, GPS)	Mobile with spatial headphone	Natural (Audio-based)	Indoor and outdoor
Madsen and Madsen [2016]	Reconstruction	Sensor-based (IMU)	Mobile	Tangible	Indoor and outdoor
Vanoni et al. [2012]	Reconstruction	Markerless	Mobile	Tangible	Indoor and outdoor

Table V. : The surveyed VR applications in the CH domain and their purpose and the enabling technologies they adopted

Application	Purpose	Tracking	Display	Interface	Setting
Wojciechowski et al. [2004]	Virtual museum	No pose tracking (pre-rendered respective)	Desktop screen	Web-based (Mouse and keyboard)	Non-immersive
Zara [2004]	Virtual museum	No pose tacking	Desktop screen	Device-based	Non-immersive
Laycock et al. [2008]	Reconstruction	No pose tracking	Desktop	Device-based	Non-immersive
Richards-Rissetto et al. [2014]	Education	No pose tracking	Screen/wall	Device-based	Non-immersive
Baldissini and Gaiani [2014]	Education	No pose tracking	Desktop	Device-based	Non-immersive
Gaitatzes et al. [2001]	Education	Electromagnetic	Back-projected screen	Device-based	Semi-immersive
Bruno et al. [2010]	Virtual museum	No pose tracking	Stereoscopic screen	Device-based	Semi-immersive
Haydar et al. [2011]	Virtual museum	Optical	Large Screen with LCD glasses	Device-based	Semi-immersive
Pietroni et al. [2013]	Reconstruction	No pose tracking	Screen/wall	Sensor-based (through natural gesture)	Semi-immersive
Richards-Rissetto et al. [2014]	Education	No pose tracking	3D stereo display)	Sensor-based	Semi-immersive
Hsieh et al. [2014]	Virtual museum	No pose tracking	Projector	Hybrid (Device-based and sensor-based)	Semi-immersive
Marton et al. [2014]	Exploration	Custom-designed (Image-based)	Back-projected screen	Device-based	Semi-immersive
Reunanen et al. [2015]	Reconstruction	No pose tracking	Back-projected stereo screen with goggles	Sensor-based (through natural gesture)	Semi-immersive
Bustillo et al. [2015]	Education	Hybrid (optical and markerless)	Projector	Device-based	Semi-immersive
Gaitatzes et al. [2001]	Education	Electromagnetic	CAVE	Device-based	Fully immersive
Acevedo et al. [2001]	Exploration	Hybrid (IMU, optical/electromagnetic)	CAVE	Device-based	Fully-immersive
Gutierrez et al. [2004]	Reconstruction	No pose tracking	CAVE	Device-based (radio-based remote control)	Fully-immersive
Christou et al. [2006]	Virtual museum	Electromagnetic	CAVE	Multimodal	Fully-immersive
Hernández et al. [2007]	Virtual museum	Hybrid (Acoustic and Inertial)	HMD	Sensor-based	Fully-immersive
Haydar et al. [2011]	Virtual museum	Optical	HMD	Device-based	Fully-immersive
Barsanti et al. [2015]	Virtual museum	Hybrid (IMU and optical)	HMD	Sensor-based	Fully-immersive
Katsouri et al. [2015]	Virtual museum	Optical	CAVE	Device-based	Fully-immersive

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