AUGMENTED REALITY CHALLENGES FOR CULTURAL HERITAGE

Jacob Rigby and Shamus P. Smith

Working Paper Series, Number 5, November 2013

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

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Jacob Rigby
School of Engineering and Computing Sciences
Durham University
Durham DH1 3LE, United Kingdom
jake@jakerigby.com

Shamus P. Smith
AIR Research Group
School of Electrical Engineering and Computer Science
The University of Newcastle
Callaghan, NSW 2308, Australia
shamus.smith@newcastle.edu.au

ABSTRACT

Augmented Reality (AR) technology can provide a novel and interesting approach for presenting cultural heritage content to the general public. Recent advances in AR research and the quick uptake of powerful mobile devices now means AR systems are a viable option for heritage institutions, but there are still many challenges that must be overcome before high-quality AR experiences are commonplace. This paper examines published attempts at bringing AR systems to the heritage sector, and highlights and discusses the ongoing trends and challenges that are faced in this area.

1 Introduction

Cultural heritage sites and museums are tasked with providing information about the past to members of the public in a clear and easily digestible manner, and in a way that does not require large amounts of the visitors' time. However, there are challenges to overcome to achieve this - walls of text overwhelm visitors, complex and specialist language is used where the readers have only a passing interest, and uninteresting pictures fail to engage. For this reason, the heritage sector often seeks new ways to engage visitors with their sites, and is often keen to harness technology to achieve this. Previous methods have included static computer kiosks to provide information to visitors (Economou, 1998), audio tour guides (Gebbensleben et al., 2006), mobile device-based tour guides (Abowd et al., 1997; Cheverst et al., 2000; Bellotti et al., 2002), and even robot tour guides (Burgard et al., 1998; Thrun et al., 2000).

Augmented Reality (AR) offers a novel and interactive way of presenting information to visitors. An AR system is a system that enriches, or “augments”, the real world with computerised information and objects (see Figure 1). Milgram et al. (1995) defined the Reality-Virtuality continuum, a taxonomy for all Virtual Reality (VR) based systems , which encompasses everything from *reality* (the real world) to complete *virtuality* (a completely immersive, entirely virtual world). According to their classification, AR is a type of *Mixed Reality* that describes any combination of reality and virtuality (see Figure 2). It should also be noted that their definition is not tied to a particular type of hardware, notably Head-Mounted Displays (HMDs), which have been a popular choice for AR systems.

Figure 1: A mobile Augmented Reality application showing a ruined building superimposed with an intact version.

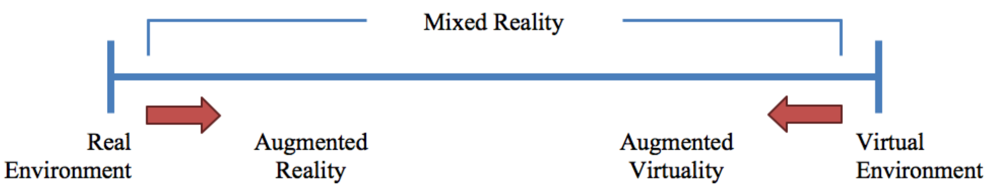

Figure 2: The reality-virtuality continuum (adapted from Milgram et al. (1995)).

Azuma (1997) also notes that AR is not tied only to HMDs. Azuma builds upon the definition, and observes that in addition to being a blend of the real and virtual, AR should be interactive in real time and registered in 3D. Azuma considers that, although AR is most commonly associated with augmenting the users' sense of sight, it can also cover the other senses such as hearing (Bederson, 1995; Harma et al., 2004).

This article focuses on the application of AR to the cultural heritage domain, and covers common approaches taken and issues that arise. Only systems and technologies that appear in published literature are discussed. This section gives a general introduction to AR and cultural heritage. Section 2 shows how cultural heritage sites can be broadly divided into indoor and outdoor categories, and discusses the challenges faced from a location perspective. Section 3 provides an overview of some common approaches to tracking in AR systems. Section 4 presents examples of the different hardware used in cultural heritage AR systems, and Section 5 presents common software toolkits and frameworks used to aid development. A summary of the trends and challenges faced in the future for different stakeholders is given in Section 6.

1.1 Augmented Reality for Cultural Heritage

The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines a cultural heritage as the following (UNESCO, 1972):

Monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;

Groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science;

Sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view.

This definition has since been broadened to also include artefacts, works of art, etc., such as those commonly found in museum exhibitions (Cernea, 2001, p.2). In this article, the term *cultural heritage site* refers to any site of cultural significance. Cultural heritage sites can be broadly categorised into two groups - outdoor and indoor. Indoor sites often take the form of museums and visitor centres, where historic artefacts are displayed for the general public. An outdoor site could simply be a field where buildings once stood, or could be an entire city consisting of many (still intact) buildings.

There are an increasing number of applications for using AR for cultural heritage, including tour guides (Miyashita et al., 2008), virtual museums (Wojciechowski et al., 2004), serious games (Bostanci and Clark, 2011), and monument reconstruction (Vlahakis et al., 2002). One reason why AR is presenting itself as a feasible technology for the heritage sector is that it is now possible to develop applications for consumer-level mobile technology - many people now carry a powerful, lightweight, networked device in the form of *smart phone* and tablet computers. These devices are being purchased by an increasing number of people, and online distribution platforms such as Apple's App Store provide an easy way for developers to deliver their software to users. Thus expensive specialist hardware need not be purchased by the heritage sites themselves, and large static computer kiosks need not take up often valuable exhibition space. Outdoor sites could particularly benefit, as in the past such systems may not have been possible due to concerns over weatherproofing and vandalism of installations.

2 Location Issues

Both indoor and outdoor sites present many of the same challenges that must be addressed to successfully implement AR systems, including content acquisition (Pavlidis et al., 2007), content storage and categorisation (Liu and Tseng, 2004), tracking and calibration (Azuma, 1999), marker placement, usability (Gabbard and Swan, 2008), and ergonomic issues (Baber et al., 1999). However, there are different issues that must be overcome that are specific to either indoor or outdoor sites.

2.1 AR for Indoor Heritage Sites

Previous applications of Augmented Reality to indoor cultural heritage sites have often taken the form of *virtual museums*, where visitors use AR technology to view objects that may otherwise be inaccessible to them. This may be due to the value or fragility of such objects, or simply due to space limitations within the museum or because the physical object is at another museum. A prominent example of this is the European Commission-funded ARCO project (Wojciechowski et al., 2004), that was designed to provide museum curators with a complete system to facilitate the creation and exhibition of a virtual museum using both Virtual Reality and Augmented Reality techniques, from content acquisition, to content management, to content presentation. Models are acquired using photogrammetry techniques[1], which are then stored in a database where they are categorised and managed. Exhibitions are presented either via a web browser (i.e., VR) or on location (i.e., AR). The AR portion of the system uses pre-fabricated 3D models from the database combined with fiducial markers[2] to allow visitors to manually inspect artefacts. Visitors are able to manipulate the objects via manipulation of the markers themselves, allowing for rotation and adjustment of zoom level of the object which would generally not be possible in a “glass case” exhibition. Multiple objects can be viewed simultaneously, and users can select which objects are shown and which are hidden, which allows for a meaningful comparison of objects. Part of the ARCO system was also modified and presented separately by Liarokapis and White (2005). A similar application of AR was implemented by Caarls et al. (2009), who extended the concept with the addition of rapid-prototyped clones of objects which were created with a 3D printer and combined with markers. This allowed visitors to touch and manipulate these prototypes, which were then augmented with 3D renderings. For an in-

[1] Photogrammetry is the practice of extracting measurements from photographs (Linder, 2009, p.1). In this context, these measurements are used to create 3D models.

[2] Fiducial markers are planar markers which serve as a real-wold placeholder for a virtual object - a marker is detected by the system and the correct virtual object is superimposed over it (see Section 3.1).

depth discussion of virtual museums, see (Styliani et al., 2009) and (Carrozzino and Bergamasco, 2010).

While fiducial markers can provide adequate tracking in situations where the camera has a good view of the marker and is not subject to constant and dramatic relocation, tracking for larger areas requires larger markers to be used and greater numbers of markers to maintain accurate position tracking. However, the placement of such markers may not be desired due to aesthetic implications, or may not be allowed if it requires placing markers on features of a protected site.

Even though the *virtual museum* concept, in which 3D models of artefacts are exhibited, is a popular one, it is not the only application of AR for indoor heritage sites and museums. Miyashita et al. (2008) also presented an indoor AR system for museums, but it was not for exhibiting digital models. Their system was developed for the Louvre, in Paris, for a temporary exhibition on Islamic art. It consisted of an *artwork appreciation* component, which provided 3D information about important parts of the artwork to the user directly in front of the exhibition via a PC station and hand-held component; and a *guidance* component which guided users through the museum using an animated character via an ultra-mobile PC (UMPC). Due to the use of fiducial markers being disallowed, the project utilised a highly accurate (within 1mm) marker-less tracking approach that performs well under the low-lighting conditions that are common in such exhibitions. The indoor portion of the Cultural Heritage Layers system presented by Zöllner et al. (2009a) also did not serve as a method of exhibiting artefacts, but instead allowed users to view a table top satellite image of Berlin augmented with a 3D model of the Berlin Wall and urban developments from 1940-2008. The same technology was used in conjunction with the Rome Reborn project[3] to present 3D Roman monuments which were augmented over a large floor map. Users would walk over the map and point a handheld device at points of interest, which would then superimpose the 3D replicas on screen (Zöllner et al., 2009b).

The main issues affecting the design of AR systems for indoor sites are those of marker placement if using marker based tracking, and ensuring that systems are easy to use for all age groups and levels of computer literacy. It is also important to ensure that the hardware used is powerful enough to support AR applications, and that equipment is robust if being lent to the public.

2.2 AR for Outdoor Heritage Sites

Developing AR systems for outdoor applications is arguably more difficult than it is for indoor applications (Azuma, 1999). The environment and resources, such as lighting conditions and electrical power, cannot be as tightly controlled, and hardware cannot usually be left outdoors. This typically means that mobile computer systems must be used, which can be uncomfortably heavy to wear and expensive if it is a wearable system combined with a head mounted display (HMD). The lack of ideal conditions often means that marker-based tracking systems cannot be used, which leads to a reliance on other methods, such as those based on Global Positioning System (GPS) and inertial sensors, which can be inaccurate. Nevertheless, numerous systems for outdoor sites have been successfully developed and implemented.

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[3] http://www.romereborn.virginia.edu/ [last access 16th October 2013].

A significant example of an application of AR to outdoor sites is the ARCHEOGUIDE project (Vlahakis et al., 2002), which used a HMD and wearable computer combination to guide the user through an Ancient Greek temple site. The system also used a tablet computer to display location-sensitive information to the user, such as pre-rendered 3D reconstructions and images of archaeological finds, which are streamed to the device via a wireless network. The project was successfully deployed in 2001, using off-the-shelf hardware components. However, during testing it was found that the hardware was uncomfortable to wear for long periods (Vlahakis et al., 2001).

The Augurscope project (Schnädelbach et al., 2002) took a different approach. There were no wearable components as it combined a wheeled tripod with a computer and camera system, allowing users to wheel the device around a castle site in Nottingham, England. However, despite its mobility and that fact that it was designed to be used while moving, it was found that users were reluctant to move the device (perhaps due to the size and weight of the device and uneven ground surface), and that groups of people of different heights meant constant adjustment of the device was necessary. With these issues in mind, the Augurscope was later refined into the Augurscope II (Schnädelbach et al., 2004), with improvements in mobility, accessibility and shading from sunlight, where more people were willing to move it around the site. A summary of the Augurscope project can be found in (Schnädelbach et al., 2006).

Another outdoor system using mobile technology is MARCH (Choudary et al., 2009). Unlike ARCHEOGUIDE, the then contemporary (year 2009) consumer mobile phones had the power and features to implement an AR system. The MARCH system was developed for the Gargas prehistoric cave site in France, and uses AR to superimpose enhanced images of cave painting over the remains, which can be difficult to interpret. As the system uses a mobile phone, it is completely mobile and does not suffer from the comfort problems encountered by ARCHEOGUIDE.

The Mobile Augmented Reality Tour (MART) system (Seo et al., 2010) also demonstrates a mobile outdoor augmented reality system. The researchers used popular tourist spots in Gyeongbokgung, Korea to test the system's tracking technology. Using their system, 3D characters are correctly superimposed in numerous environments. However, even though the technology is targeted at mobile phones, the results presented were obtained from a prototype that ran on a laptop.

The main issues faced in designing AR systems for outdoor sites are those of tracking effectively without the use of markers in an environment that may be devoid of features to use for tracking, and also ensuring any apparatus used is weather-proof and vandal-proof. Also, as with indoor sites, hardware used must be powerful enough to support AR applications. There is also the issue of making software available to visitors - if the user has to download and install software then there needs to be infrastructure in place to allow this.

3 Tracking

For an augmented reality system to work effectively, the position of the device in the world must be accurately tracked so that virtual objects can be superimposed in the correct location. Augmented reality generally requires tracking in 6 degrees of freedom (6DoF) - x, y, and z combined with pitch, roll, and yaw - to enable digital data to be superimposed seamlessly into the real world, though there are some exceptions (Park and Park, 2010). A number of methods are popular, including marker-based, inertial, optical, and location-based. However, none of these technologies are perfect. For example, GPS positioning can be too inaccurate; inertial sensors are subject to drift (loss of accuracy over time); and optical methods can be computationally expensive. As such, hybrid approaches that make up for the shortcomings of using a single technology are common (State et al., 1996; You and Neumann, 2001; Reitmayr and Drummond, 2006, 2007). The suitability of each method depends on many factors, primary of which is the domain location (some methods are more suited to indoor than outdoor and vice-versa), but also target hardware, and how sensitive the domain is to modification.

It is important to distinguish tracking from calibration. Calibration refers to the initialisation phase of a tracking system (for example, determining the initial position of a device using GPS), and tracking refers to the continued re-evaluation of the scene and device position so that objects are correctly located. However, many of the papers reviewed for this article to do not discuss calibration in much detail, or it is discussed as part of the tracking system and not explicitly mentioned. Also, sometimes calibration is not actually a separate initial phase of the tracking process, but happens during every step of the tracking process. An example of this is in marker-based tracking systems where location calibration occurs at every frame.

3.1 Marker-based Tracking

Planar marker tracking systems employ the use of a camera to detect markers placed in the real world that are used to describe the position and orientation of virtual objects. The use of fiducial markers as a means of tracking is widely used in the field of AR in general, due to its efficient performance and the ease and cost effectiveness with which markers can be produced and placed. While this is still considered a method of optical tracking, due to it being so common and such a large category we categorise it as distinct from other optical methods, which are described in Section 3.3. There are some disadvantages to using marker-based tracking: it is (i) only suitable under good lighting and visibility conditions; (ii) generally not feasible for outside use; and (iii) the markers may not be aesthetically pleasing or permitted for use. To make markers less intrusive, it is possible that a marker system based on watermarks could be used (Lee et al., 2007), or even completely invisible markers using infrared ink (Park and Park, 2004). Tool support for marker-based tracking solutions are described in Section 5.1. Cultural heritage AR systems that have used marker-based tracking include the ARCO project (Wojciechowski et al., 2004), the system presented by Caarls et al. (2009), and MARCH (Choudary et al., 2009).

The ARCO project (Wojciechowski et al., 2004) used a fiducial marker based system for its tracking system, which was based on that of ARToolkit (see Section 5.1). As this was to exhibit virtual objects, the placement of markers was acceptable, as it did not involve placing them on walls or other features.

The system presented by Caarls et al. (2009) also used a marker-based tracking system, which used markers very similar to those of ARToolkit. The MARCH system (Choudary et al., 2009) used a custom marker-based tracking system with unique *colour target* markers (Coughlan et al., 2005). The marker detection system was designed to be run in real time on mobile phones, but the actual MARCH system achieved performance of only 14 frames per second.

3.2 Inertial Sensor-based Tracking

Tracking via inertial sensors in a device (for example the gyroscopes and accelerometers found in many modern mobile phones) provides a method of tracking that is entirely internal to that device, i.e., the sensors are not reliant on any markers or other electronic devices after any initial calibration or set-up stage. However, inertial sensors are subject to drift (Zhang, 2009; Muthukrishnan et al., 2010), and some are sensitive to environmental changes such as electromagnetic interference (Turner, 2009, p. 204). Also, as an entirely inertial system has no visual input, it cannot account for object occlusion[4]. Tracking entirely by inertial sensors is usually combined with another method to increase accuracy. It is rare in AR and no example could be found within the cultural heritage domain. Commonly used inertial sensors are gyroscopes, which measure orientation, and accelerometers, which measure acceleration. These are commonly paired to allow accurate position and orientation tracking, both in AR and for a number of other applications such as ship navigation (Kaplan and Hegarty, 2006, p.642).

3.3 Optical Tracking

Optical tracking methods typically achieve tracking by detecting environmental geometry features, like building corners or picture frame edges, such as the Speeded Up Robust Feature (SURF) (Bay et al., 2008) and Scale-Invariant Feature Transform (SIFT) (Lowe, 1999) methods (Fritz et al., 2006; Bay et al., 2006), and other techniques that compare the current scene to reference images (Takacs et al., 2008; Vlahakis et al., 2002). However, this is not always possible if there are no easily-distinguishable features in the environment, such as an archaeological site in a field (Neumann et al., 1999). Cultural heritage AR systems that have used optical tracking include the Interactive Museum Guide (Bay et al., 2006), the GAMME project (Tillon et al., 2010), Cultural Heritage Layers (Zöllner et al., 2009a), and the Augmented Reality Presentation System for Remote Cultural Heritage Sites (Zöllner et al., 2009b).

The Interactive Museum Guide (Bay et al., 2006) utilised SURF, where the objects in the current scene are compared to a database of images of objects and matched to their respective “interest points”. The image with the greatest number of matches is selected in order to attempt to select the correct object that the user is looking at. This approach does not require objects in the scene to be compared to photos of each object in isolation, which can increase production speed of the database of images. It was also found to work with a low quality camera, and does not need colour images.

The Cultural Heritage Layers system (Zöllner et al., 2009a) utilised a similar entirely optical tracking system which used a two-phased approach. An initialisation stage was used for calibration and initialisation, where input from the camera is analysed to see if it matches a number of pre-specified “spots”, and a tracking phase was used to update the position of objects in every frame after a spot has been detected. Knowledge of the spots is supplied to the system in the form of reference

[4] Object occlusion in this context refers to when a real-world object is placed in front of a virtual one. The desired result of this is the virtual object being partially or totally obscured by the real-world object.

images, and for each of these a tree data structure of easily detectable points is created and stored. This can be done before the system is used. Their tracking system had two modes, one for indoor environments and one for outdoor. The indoor tracking mode was intended for use with objects close to the user, and would accurately track in 6DoF. The outdoor mode assumed that objects would be far away and assumed a panoramic view around the user and because of this would only track in 3DoF to measure the change in rotation of a stationary user (Zöllner et al., 2008). The system used only 2D overlays as opposed to 3D models in an effort to maximise performance, but still only ran at 15 frames per second.

3.4 Location-based Tracking

This category of tracking relies on satellites or beacons to calculate the position of the device. GPS is another commonly used method of tracking for outdoor applications. GPS requires a GPS receiver and un-occluded line-of-sight to four or more GPS satellites to calculate the device's position. It is therefore only suitable for outdoor use but often performs poorly in urban environments (Gartner and Rehrl, 2008, p.338). Another disadvantage of GPS is that most consumer-grade receivers are only accurate to within a few metres, and can often be out by as much as 20 metres (Lehtinen et al., 2008), and such receivers integrated into mobile devices are just as inaccurate (Ben Abdesslem et al., 2009). This lack of accuracy means that GPS is rarely used as the sole tracking technology, but is commonly paired with another technology so that the GPS provides coarse-grain tracking to give a rough idea of location, that is refined by the other tracking method to provide the necessary accuracy. The only AR cultural heritage system found that used only GPS for tracking was the outdoor portion of the Cyberguide system (Abowd et al., 1997).

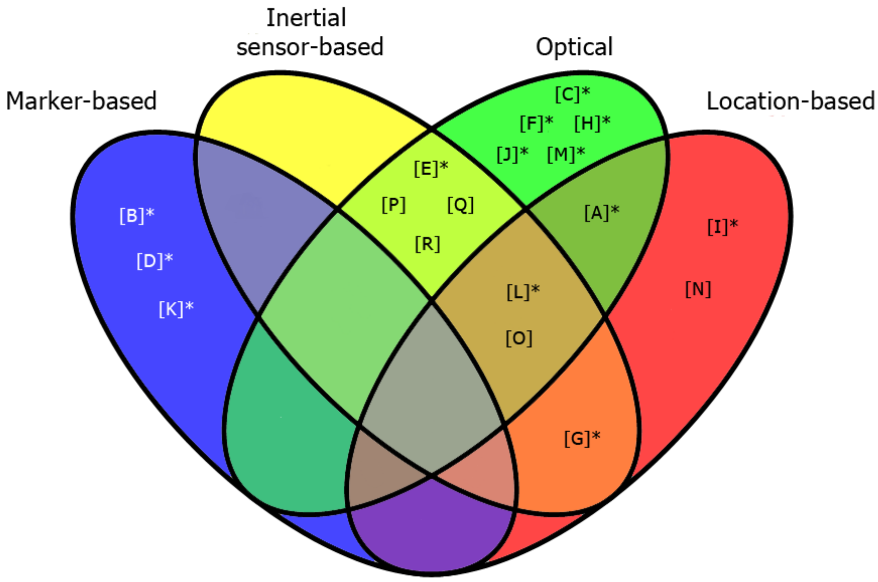
Infrared beacons can also be used as a means of tracking (Ribo et al., 2001). A cultural heritage system that used this approach is the indoor portion of the Cyberguide tour guide system (Abowd et al., 1997), where multiple beacons were placed around an indoor setting. It is also possible to use wireless networks as a means of tracking, where wireless network devices act as beacons to allow for the calculation of location (Howard et al., 2003; Peternier et al., 2006). However, no examples could be found in the cultural heritage domain.

3.5 Hybrid Tracking

Hybrid tracking systems are common as they ensure the high-accuracy of position tracking needed for AR, and using one tracking method in tandem with one or more others can make up for technological shortcomings in each tracking method respectively. Cultural heritage AR systems that have used hybrid tracking include ARCHEOGUIDE system (Vlahakis et al., 2002), the Augurscope (Schnädelbach et al., 2002), the Augmented Reality Museum Guide (Miyashita et al., 2008), and MART (Seo et al., 2010). The ARCHEOGUIDE system utilised a custom optical tracking approach combined with GPS position data. The GPS receiver would first provide a rough estimation of position and viewing angle, and then the optical tracking algorithm would further refine this by attempting to match the users' current view to a series of images stored in a database on a frame-by-frame basis. This approach supported 15 frames per second at a resolution of 320 x 240 pixels.

The Augurscope used a hybrid GPS and inertial sensor system. The results were found to be satisfactory, but there were problems with the accuracy of the GPS, which was only accurate to within 2-4 metres and had a 2 second update time, meaning that without any further software smoothing the user would experience a lot of jittering.

The MART system combined GPS, inertial sensors and optical tracking. Its tracking model consisted of a sensor-based tracking flow which encompasses readings from GPS and inertial sensors, and a vision-based tracking flow that matches the current camera scene to a database of reference images. These tracking flows can then be combined to make a hybrid tracking flow, which also incorporates other readings, such as those from light sensors.



System	Tracking	Key
ARCHEOGUIDE (Vlahakis et al, 2002)	Optical, GPS	[A]*
ARCO Project (Wojciechowski et al, 2004)	Marker-based	[B]*
An augmented fine-art exhibit (Tillon et al, 2010)	Optical	[C]*
Augmented Reality for Art, Design and Cultural Heritage (Caarls et al, 2009)	Marker-based	[D]*
Augmented Reality Museum Guide (Miyashita et al, 2008)	Optical,inertial	[E]*
Augmented Reality Presentation System for Remote Cultural Heritage Sites (Zöllner et al, 2009b)	Optical	[F]*
Augurscope (Schnädelbach et al, 2002)	GPS, Inertial	[G]*
Cultural Heritage Layers (Zöllner et al, 2009a)	Optical	[H]*
Cyberguide (Abowd et al, 1997)	IR (Indoor), GPS (outdoor)	[I]*
Interactive Museum Guide (Bay et al, 2006)	Optical	[J]*
MARCH (Choudary et al, 2009)	Marker-based	[K]*
MART (Seo et al, 2010)	Optical, inertial, GPS	[L]*
Mixing virtual and real scenes in the site of ancient Pompeii (Papagiannakis et al, 2005)	Optical	[M]*
(Peternier et al, 2006)	WiFi	[N]
(Reitmayr and Drummond, 2007)	Optical, inertial, GPS	[O]
(Reitmayr and Drummond, 2006)	Optical, inertial	[P]
(State et al, 1996)	Optical, inertial	[Q]
(You and Neumann, 2001)	Optical, inertial	[R]

Figure 3: Venn diagram and legend showing tracking technologies used by AR systems considered in this article. Items marked with an asterisk (*) are systems specific to the cultural heritage domain.

3.6 Summary

Figure 3 shows the tracking technologies used by the example systems detailed in this article. This shows that cultural heritage AR systems generally favour the use of marker-less or optical tracking. It can also be seen that systems that use marker-based tracking do not tend to use any auxiliary tracking methods. This may be because marker-based tracking is only chosen where the lighting conditions can be controlled, and when the user is intended to be up close to the objects in the system, for example in a museum setting - because of this, marker-based methods alone may be perfectly adequate. The diagram also shows that tracking systems that combine three or more tracking technologies are rare.

4 Hardware

At a basic hardware level, an AR system requires four components: a computer system; a camera; a display; and some kind of tracking mechanism (although this may be a software component). There are three main categories of hardware used in AR systems: fixed computer systems; wearable computer systems; and mobile devices.

4.1 Fixed Computer Systems

AR systems can be used with static computer terminals with attached cameras. Some examples in the cultural heritage domain are the museum guide system for the Louvre (Miyashita et al., 2008), where a small industrial camera was used in conjunction with a PC for their presentation room, and the MovableScreen (Zöllner et al., 2009b), which mounts a 24" iMac on a pillar that can be rotated 360 degrees. The advantages of such systems include a potentially stable power supply and network connection if mains power and a wired connection is used, and they are generally easy to develop for as they are often simply standard desktop PCs. They are also able to be used by more than one user at a time so the AR experience can be shared amongst families or groups of visitors. Disadvantages include lack of mobility and the large amount of space they take up.

Although the Augurscope (Schnädelbach et al., 2002) was designed to be moveable, it was essentially a fixed system mounted on a wheeled tripod (the system was not designed to be used when moving the tripod; the wheels served only as a method to move between locations). The system used a laptop computer to minimise weight, and an attached camera.

4.2 Wearable Computer Systems

While not required, many AR systems traditionally used HMDs as the display device (Azuma, 1997). Two types of HMDs are available today: optical see-through, where a semi-transparent surface placed in front of the eyes allows the user to see both the real world and have digital images reflected into their eyes; and video see-through, where one or more cameras provide a video feed of the real world, which is then combined with digital images (Rolland and Fuchs, 2000). Unfortunately HMDs can be very expensive and uncomfortable, and usually have to be paired with some kind of wearable computer. Nowadays, integrated displays such as those featured in smart phones and tablets are preferable because of their favourable size, inexpensiveness, and durability.

Cultural heritage systems that have used wearable computers include ARCHEOGUIDE (Vlahakis et al., 2002) and the system developed for Pompeii by Papagiannakis et al. (2005). However, for many of the systems that used wearable computers, the then-current mobile hardware such as PDAs, tablets and smart phones were not powerful enough, so to provide enough computational power this often meant a high-end laptop would need to be used, which would often be heavy and uncomfortable (Azuma et al., 2001). However, advances in off-the-shelf consumer hardware now mean that contemporary mobile devices can provide enough computing power for such applications.

4.3 Mobile Devices

Due to ubiquity of powerful mobile devices such as smart phones and tablets, mobile devices are becoming popular platforms for AR systems. Table 1 shows the specifications of four popular mobile devices (a number of similar devices are available from competing manufacturers). These devices also feature accelerometers and gyroscopes suitable for position tracking in 6DoF. Their powerful features make all these devices suitable devices for a high-quality AR experience. This means that, as visitors will already own their own devices, cultural heritage institutions that take of advantage of this will not have to procure expensive specialist equipment to lend to visitors, and greater homogeneity of hardware platforms makes it easier to develop software. However, with multiple software platforms being popular (such as Android, Windows and iOS) it can mean that multiple versions of the same software need to be produced even though the hardware configuration is largely similar.

Device	CPU	RAM	Display	Cameras
Apple iPhone 4S	800MHz dual-core	512MB	3.5", 640 x 960 px	8 MP back, 0.3 MP front
HTC Rezound phone	1.5GHz dual-core	1GB	4.3", 1280 x 720 px	8 MP back, 2 MP front
Apple iPad 2	1GHz dual-core	512MB	9.7", 1024 x 768 px	0.7 MP back, 0.3 MP front
Samsung Galaxy Tab 10.1	1GHz dual-core	1GB	10.1", 1280 x 800 px	8 MP back, 2 MP front

Table 1: Specifications of example mobile hardware

The presence of both forward- and backward-facing cameras on these devices as opposed to only a traditional backward-facing one is significant: a backward facing camera only allows the user to see an augmented view of the scene in front of them (a magic window or magic lens), whereas devices with forward facing cameras also allow the user to see and augmented view of themselves (a magic mirror). This would allow visitors to heritage sites and museums to virtually “try on” historical clothing, or even wear suits of armour, and enable them to view themselves wearing such items as well as viewing their friends and family, making for a more collaborative experience which aligns itself well with the family audience that many heritage sites aim to attract (Fiala, 2007)

Example AR systems for cultural heritage that have used mobile hardware include the Cultural Heritage Layers system (Zöllner et al., 2009a) that utilised a Sony UMPC (ultra mobile personal computer) as a mobile device for users, the museum guide system for the Louvre (Miyashita et al., 2008) that utilised a Fujitsu UMPC, the MARCH system (Choudary et al., 2009) system that utilised a Nokia N95 mobile phone.

While more powerful hardware is becoming ubiquitous, real-time processing for AR systems (especially tracking and rendering) can still be very computationally expensive (Wagner and Schmalstieg, 2009). To combat this, it is possible to take advantage of the networking features of some devices to move a lot of the processing to a more powerful server (Gausemeier et al., 2003;

Wagner and Schmalstieg, 2003). However, this obviously relies on the presence of a server and a stable network infrastructure.

In addition to the hardware used by the users, it may also be necessary to install other hardware at a site, for example to provide infrastructure for networking or tracking. This obviously has cost implications, and it may not be desirable to leave expensive equipment outside in all weather conditions or at unmanned sites. For an in-depth discussion of mobile technologies for AR, see (Papagiannakis et al., 2008).

5 Software

Many past cultural heritage AR applications have used mobile devices, and designers typically chose client-server architectures, storing content on a central server and streaming it to the user's device over a network (Vlahakis et al., 2002; Wojciechowski et al., 2004). This makes sense if there is a lot of content as mobile devices are often lacking in storage space, and it means that only content specific to the user's location and interests need be streamed (assuming the system is aware of them) (Davies et al., 2001). It is possible to view the structure of an application from a development perspective in layers, as in Figure 4. The operating system and APIs used are largely dependent on the choice of target hardware (for example, if developing for the Apple iPhone, the Apple iOS and Apple development tools must be used) but there is more freedom when it comes to toolkits. There are many toolkits available to aid the development of AR applications, mainly to provide robust tracking solutions without the need to code a system from scratch. When developing for AR applications, as with any other kind of development, a number of decisions must be made including those regarding software architecture, target platforms, toolkits, etc. Many AR systems use custom tracking methods, but some developers make use of toolkits to save time. A good analogy is that of computer game design, where it is common for game developers to use a licenced game engine, as well as other middleware, which has been developed by another company. This allows the developers to focus more on content creation and reduce development time, but there are the downsides of less customisation and licence fees. Some commonly used toolkits are presented in the following section, which focuses mainly on tools that are available to use for free.

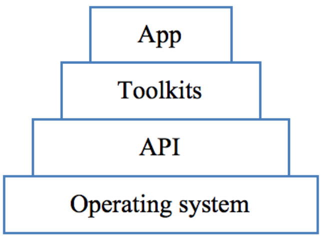


Figure 4: The layered structure of an application.

5.1 Tool Support

A common library used for marker-based tracking is ARToolkit[5], a free, multiplatform C and C++ tracking library which supports both video- and optical- see through AR. It is well supported by documentation and tutorials, and there is an active user community who are able to communicate

[5] http://www.hitl.washington.edu/artoolkit/ [last access 16th October 2013].

via mailing lists and forums. The library works by converting the video input into a binary image and detecting the large black frame around the edge of the marker. Figure 5 shows an example ARToolkit marker. ARToolkit then calculates the relative position and orientation of the marker to the camera and matches the symbol on the marker to those stored in pattern files (for storing 12 possible orientations of the marker) to select the correct virtual object. The object is then transformed to align it with the marker and then rendered[6]. Markers are customisable by the developer, so images relevant to the application domain can be used. There are, however, some drawbacks to ARToolkit. It often detects markers where there are none (a false positive reading) and often confuses markers (inter-marker confusion). Despite some shortcomings, ARToolkit is arguably the most popular software toolkit for developing AR applications. It is available for numerous platforms and hardware configurations including popular mobile platforms such as Google's Android and Apple's iOS. It is open source and free to use for non-commercial use, but also commercially licenced for professional use.

Figure 5: Example ARToolkit marker.

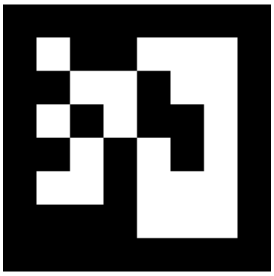


Figure 6: Example ARTag marker.

ARToolKitPlus, an extended version of ARToolkit, was designed as its successor (Wagner and Schmalstieg, 2007), but both libraries were continually developed alongside each other. ARToolKitPlus has itself since been succeeded by the Studierstube Tracker (Schmalstieg et al., 2002), and Studierstube ES (Schmalstieg and Wagner, 2008) for embedded systems and mobile phones, but these are not publicly available.

ARTag is another marker-based tracking library, which was created in an attempt to address some of the shortcoming of ARToolkit - namely the high rate of false positives and frequent inter-marker confusion. ARTag differs from ARToolkit in that it does not match the images to pattern files, but instead uses a digital symbol method which encodes a binary code with checksums and error correction redundancy, inspired by the Data Matrix barcode system (Fiala, 2004). Figure 6 shows an ARTag marker. The ARTag library is free for non-commercial use.

Another derivative of ARToolkit is OSGART (ARToolkit for OpenSceneGraph) (Looser et al., 2006), which combines ARToolkit functionality with that of OpenSceneGraph[7], a 3D graphics API which allows a 3D scene to be represented in a graph data structure. OSGART provides tracking functionality as well as advanced visualisation features, such as shadows and reflections. It is cross-platform, and a free version is available under the GPL licence for non-commercial use. The Designer's Augmented Reality Toolkit (DART) (MacIntyre et al., 2005) provides a high-level way of

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[6] http://www.hitl.washington.edu/artoolkit/documentation/userarwork.htm [last access 16th October 2013].

[7] http://www.openscenegraph.org/ [last access 16th October 2013]

developing rapid prototypes of AR software by using a scripting language. It is aimed more at designers than computer scientists, and attempts to provide an easy way of creating content and making AR applications without the need for in-depth technical knowledge.

6 Trends and Challenges

As research has intensified over recent years and technology has improved, AR now presents itself as a feasible option to the heritage sector. A number of state- and EU-funded projects have seen fruition in the form of ARCHEOGUIDE (Vlahakis et al., 2002), the ARCO project (Wojciechowski et al., 2004), iTacitus[8], and the GAMME project (Tillon et al., 2010). This shows that AR is not just suitable for research environments but also for real museums and heritage sites, and that it is being taken seriously by government funding councils as a method of bringing heritage to the masses. However, there are still many challenges that must be addressed before AR becomes commonplace in the heritage sector.

6.1 Technology

The most obvious trend observed is the increase in uptake and development of powerful mobile devices that make mobile AR applications possible, and the increasing number of applications for such devices that apply AR is testament to this. Due to the ever-increasing power of mobile devices and increasing interest in AR, such applications are predicted to become even more pervasive. However, while many potential visitors may own the necessary AR-enabling hardware, this still only represents a small percentage of potential visitors. Many mobile devices are expensive, luxury items, and there can be accessibility issues associated with this. Most museums and heritage sites are keen to attract as many people as possible, and if users must purchase expensive hardware to get the full experience then this does not present a high level of accessibility. The issue of cost is also an important one for both the visitor and the heritage site or museum. Most heritage sites and museums try to attract families to visit together, but few families can afford to buy every family member an expensive tablet or smart phone. From the perspective of the heritage site or museum AR systems can be expensive to develop and deploy, so they may not be cost-effective if only a small number of visitors will be using them. A solution for this is to provide hardware to loan out to visitors, but the added cost this incurs for the museum and the rate at which hardware must be replaced may not be attractive, and it may not be desirable to allow visitors to borrow expensive and delicate hardware, especially if they are to be used by young children.

6.2 Location

Many heritage sites are protected from modification of any description, and this can even extend to the placing of fiducial markers or other necessary items to facilitate AR. This narrows the choice of available technologies for some sites, meaning that marker-less AR, or other unobtrusive tracking technology, must be used. Even if the placing of markers is permitted, it can be undesired for aesthetic reasons. Many heritage sites and museums disallow the use of cameras and photography, and some disallow the use of mobile phones. If such devices are not permitted, this can preclude the use of mobile AR. A solution to this problem may be to have clearly defined zones in which the

[8] http://www.itacitus.org/ [last access 16th October 2013]

devices may be used for AR, but this could be difficult to enforce. Another problem is that visitors using devices for AR while moving can present health and safety issues. If visitors are not paying attention to where they are walking they may trip and fall, or walk into exhibits or other people. Clearly defined, uncluttered AR zones could also go some way to solving this problem.

From a technological perspective, there is still much to be achieved with regards to tracking, specifically for outdoor rural sites such as those situated in fields.

6.3 Development and Deployment

For developers and programmers, developing for AR applications can be problematic because of the lack of easy-to-use development environments tailored towards AR. The Designer's Augmented Reality Toolkit (MacIntyre et al., 2005) sought to address this problem by providing an environment to support high-level, rapid prototyping of AR systems without the need for extensive low-level programming. However, the system was designed to run on top of Macromedia (now Adobe) Director which may constrain development somewhat, as well as leading to decreased performance and a larger software footprint. No example systems using this toolkit in the cultural heritage domain could be found. However, there are increasing numbers of AR solutions available, for example Metaio AR platform[9], and it is likely that these free to use platforms will dominate cultural heritage AR deployments in the future.

The type of hardware used can also affect development time and cost. If a standard desktop PC is used, such as in a kiosk system, development is relatively easy compared to a mobile platform, as the developers are free to use any software and tools they wish and they will only need to support a single platform. If mobile hardware is to be used then developers are often constrained as to which development tools they can use, and they may be required to support multiple platforms. This in turn brings about licensing issues for software used and the software in developments - for example, developing for Apple hardware and distributing via their App Store requires the use of Apple's own development tools, as well as requiring Apple to accept the software on their terms for distribution. However there are a number of high profile projects aiming to bring AR experience to mainstream users. Examples such as Google Glass[10] are firmly targeted at the general consumer market. Access to such accessible AR hardware will increase AR opportunities over many domains.

However, there is still much to be achieved from a cultural heritage perspective. Many of the example systems in this article exist only as research projects, often as a vehicle to test new tracking technologies or hardware, instead of providing an entire system for use by heritage institutions. The majority of those working in the heritage sector are not technology experts, and curators and other heritage specialists should not be expected to have to acquire such knowledge in order to use or manage such systems. The ARCO project (Wojciechowski et al., 2004) went some way to address this by providing an entire system to facilitate inventory management and presentation, but the project does not seem to be in active development. The ARTECT tool (Koleva et al., 2009) created a high-level authoring tool for non-technical heritage workers to use, which focused on creating an

[9] http://www.metaio.com/ [last access 16th October 2013].

[10] http://www.google.com/glass/start/ [last access 16th October 2013].

experience-centred toolkit rather than a software-centred one. Multiple iterations were developed with input from domain experts, and the project was tested and found to be fit for purpose. However, development of the toolkit seems to have ceased, and only a prototype version exists for testing purposes[11]. The CHESS project[12] is a project that is also developing authoring tools for non-technical personnel, in order to allow them to create an interactive storytelling experience for a variety of audiences (Pujol et al., 2013). The project is still in progress, and the associated software tools have not yet been publicly released. Bruno et al. (2010) presented a methodology to facilitate the creation of a virtual museum in a cost-effective manner, from digitising archaeological finds to presenting them with their MNEME[13] (virtual exhibition) software system and portable hardware. However, it still required a team of specialists to digitise the objects over a lengthy three month period. Also, it used virtual reality as opposed to AR, but a similar methodology could be applied to AR exhibitions.

The majority of AR systems developed to date, including those for cultural heritage, give the user a primarily passive experience with little interaction. Tour guide systems, for example, often simply provide users with context sensitive information which requires no reaction from the user. However, some systems facilitate basic interaction with objects. The ARCO Project (Wojciechowski et al., 2004) allowed users to move markers, and the system presented by Caarls et al. (2009) allowed users to touch replicas of objects, but the user is only moving real-world placeholders and not really interacting with the software system.

One way to encourage interaction is through games. Serious games, games that are used as educational aids rather than purely for recreation, have been widely used in the cultural heritage sector (for further reading on this, see the state-of-the-art review presented by Anderson et al. (2010)), but serious games that employ AR technology have not been widely explored. AR serious games could be an extremely effective way of engaging visitors, especially children. Digital characters could not only inform visitors about exhibitions, but also ask them to complete tasks such as participating in scavenger hunts, or ask them to answer a series of questions about what they have seen. One system that did attempt an AR game in a museum environment was the Mobile Augmented Reality Quest (MARQ): Expedition Schatzsuche[14], which implemented a team-based treasure hunt-style game on top of the Studierstube ES tracking system (Schmalstieg and Wagner, 2008). However, the project ceased in 2007 and little academic literature was produced from it. Games could also allow visitors to participate in a story (much like modern-day computer games) from the moment they enter the heritage site, which could develop as they progress through the site, performing tasks as they go. Such games can be made all the more believable using today's immersive AR technology. If collaboration (or competition) between users, such as in MARQ, was also possible then it may be especially of benefit to groups of schoolchildren.

[11] http://www.cs.nott.ac.uk/~ktg/install.html [last access 5th October 2013].

[12] http://www.chessexperience.eu/ [last access 5th October 2013].

[13] MNEME is not an acronym. It is from the Ancient Greek “memory”.

[14] http://handheldar.icg.tugraz.at/marq.php [Last access 5th October 2013].

Table 2 presents the example cultural heritage systems described in this article, comparing the technologies and techniques used by each system.

Name	Indoor/outdoor	Tracking	Hardware
ARCHEOGUIDE (Vlahakis et al, 2002)	O	Optical, GPS	HMD with wearable laptop, PDA
ARCO Project (Wojciechowski et al, 2004)	I	Marker-based	Static terminal
An augmented fine-art exhibit (Tillon et al, 2010)	I	Optical	UMPC
Augmented Reality for Art, Design and Cultural Heritage (Caarls et al, 2009)	I	Marker-based	HMD with wearable PC, static terminal
Augmented Reality Museum Guide (Miyashita et al, 2008)	I	Optical, inertial	UMPC, static terminal
Augmented Reality Presentation System for Remote Cultural Heritage Sites (Zöllner et al, 2009b)	I	Optical	Rotatable fixed screen, UMPC
Augurscope (Schnädelbach et al, 2002)	O	GPS, inertial	Tripod-mounted PC
Cultural Heritage Layers (Zöllner et al, 2009a)	I/O	Optical	UMPC
Cyberguide (Abowd et al, 1997)	I/O	IR (Indoor), GPS (outdoor)	UMPC
Interactive Museum Guide (Bay et al, 2006)	I	Optical	Tablet PC with attached camera
MARCH (Choudary et al, 2009)	I/O	Marker-based	Mobile phone
MART (Seo et al, 2010)	I/O	Optical, inertial, GPS	Laptop with attached camera, mobile phone
Mixing virtual and real scenes in the site of ancient Pompeii (Papagiannakis et al, 2005)	I/O	Optical	Mobile workstation

Table 2: Overview of AR systems for cultural heritage discussed in this article.

7 Summary

This article has shown that AR systems within the cultural heritage domain are becoming more and more feasible, mainly thanks to the uptake of powerful consumer-level mobile hardware and technological improvements in tracking systems. The problems that must be overcome for such systems to be successful are also highlighted; these include the limitations of current tracking technologies (especially the lack of accurate tracking systems in outdoor environments), the difficulties of developing AR software without established standards, frameworks, and easy to use toolkits, the cost of hardware, and the cost and duration of system development and content acquisition.

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