MixAR: A MULTI-TRACKING MIXED REALITY SYSTEM TO VISUALIZE VIRTUAL ANCIENT BUILDINGS ALIGNED UPON RUINS

Telmo Adão, INESC Technology and Science (INESC-TEC) and University of Trás-os-Montes e Alto Douro (UTAD), 5000-801 Vila Real, Portugal.
Luís Pádua, David Narciso, University of Trás-os-Montes e Alto Douro, School of Sciences and Technology, 5000-801 Vila Real, Portugal.
Joaquim J. Sousa, Emanuel Peres, INESC Technology and Science (INESC-TEC) And University of Trás-os-Montes E Alto Douro (UTAD), 5000-801 Vila Real, Portugal.
Luís Agrellos, GEMA - Digital and Technology Agency, Cais das Pedras N.º 8, 4050-465 Porto, Portugal.
Luís Magalhães, ALGORITMI Center, University of Minho, 4800-058 Guimarães, Portugal.

Abstract

MixAR, a full-stack system capable of providing visualization of virtual reconstructions seamlessly integrated in the real scene (e.g. upon ruins), with the possibility of being freely explored by visitors, *in situ*, is presented in this paper. In addition to its ability to operate with several tracking approaches to be able to deal with a wide variety of environmental conditions, MixAR system also implements an extended environment feature that provides visitors with an insight on surrounding points-of-interest for visitation during Mixed Reality experiences (positional rough tracking). A procedural modelling tool mainstreams augmentation models production. Tests carried out with participants to ascertain comfort, satisfaction and presence/immersion based on an in-field MR experience and respective results are also presented. Easiness to adapt to the experience, desire to see the system in museums and a raised curiosity and motivation contributed as positive points for evaluation. In what regards to sickness and comfort, the low number of complaints seems to be satisfactory. Models' illumination/re-lightning must be address in future to improve user's engagement with the experiences provided by MixAR system.

Keywords

Mixed Reality, Multi-tracking System, Digital Cultural Heritage, Ruins Virtual Reconstruction, Mobile Augmented Reality System, Procedural Modelling.

1 INTRODUCTION

The Virtualization Continuum (VC) proposed by Milgram and Kishino (1994) consists of a representational scale concept that extends from a Virtual Environment at one end to a Real Environment at the other. In-between lies Mixed Reality (MR) that represents every environment resulting from a combination of the virtual and the real environments - with varying levels of mixture between the two - where virtual and real objects/persons may interact. In the VC, an Augmented Reality (AR) approach is placed closer to the real environment's extreme, since the real prevails over the virtual: a user visualizes the real environment with some added virtual objects. AR approaches usually have a process underlying the augmentation of virtual models upon real-environments known as tracking (Azuma, 1997), that accordingly to Narciso et al. (2015), can be divided into three main types: sensor-based, vision-based and hybrid. While the former uses tracking devices (location and inertial), vision-based tracking is characterized by a precise registration of a capturing device (e.g. camera) upon a real point-of-interest (POI). Furthermore, it can be marker-based (e.g. using fiducial tags) or markerless (relying uniquely on structural features of the real-environment). Hybrid tracking explores synergies between different tracking techniques to overcome their individual disadvantages. Selection of a proper tracking technique should be made considering conditions such as light, terrain morphology and anti-handling policies commonly found in protected spaces, such as cultural heritage sites. Regarding an Augmented Virtuality (AV) approach, it is placed closer to the virtual environment's extreme in the VC, since the virtual prevails over the real: a user visualizes a virtual environment to where some parts of the real environment were "transferred".

The VC has been explored by an increasing number of approaches being used in archaeology and in other areas related with cultural heritage. The aim is to provide accurate representations of ancient structures, especially those no longer available for observation at their full splendour due to severe or complete deterioration. Typically, Virtual Reality (VR) applications towards this focus confine the users' experience to an indoor space equipped with the necessary technology to deliver fully virtualized contents. Another possibility is to use AR to leverage virtual representations, providing indoor and outdoor experiences capable of seamlessly merging reality and virtual data in a single compelling environment, as it was demonstrated in areas such as archaeology and cultural heritage (Fritz, Susperregui, & Linaza, 2005; Stricker, Dähne, Seibert, & al, 2001). This can be particularly interesting to: (1) promote the general public participation in areas such as culture, history or archaeology, considering the digital heritage's importance in modern society and (2) provide tools to support professionals - such as historians and archaeologists - in tasks related with the study and analysis of damaged or completely destroyed ancient structures.

MixAR - an adaptive MR system - is a research and development project (reference FEDER/03880/2014, Portugal) developed in the University of Trás-os-Montes e Alto Douro (UTAD, Vila Real, Portugal) in partnership with GEMA Digital and Technology Agency enterprise (Porto, Portugal), whose main goal is to have a manageable harmony between the amount of reality and virtuality displayed in cultural heritage visitations. It is a solution capable of providing *in situ* visualization of reliable virtual reconstructions seamlessly superimposed to ruins present in the real scene that can be freely explored by the visitor. To achieve it, a methodology that balances the blend level between real and virtual scenes while the user is moving freely in an archaeological site was developed. Thus, when the visitor is outside a virtual building (outdoor scene) an AR approach (in which the real world prevails) is used; if the visitor moves into a virtual building's interior, virtuality takes over the experience, placing the visitor inside a fully synthesized environment. Transition occurs smoothly to provide a sensation of naturalness, as it was specified by Magalhães et al. (2014).

One of the MixAR components consists of an application running on a mobile AR system (MARS) (Pádua, Adão, et al., 2015; Pádua, Narciso, et al., 2015) that acquires and computes real-world context data using mobile devices' global position system (GPS), inertial sensors and camera to provide the proper MR experience, while the visitor moves within an archaeological site. Several tracking techniques in the same MR visitation are supported, providing the experience manager with the needed tools to tackle the following set of conditions: (1) real-world structures irregularity and texture homogeneity (e.g. ruins) responsible for hampering line extraction and further matching by CAD-based tracking techniques; (2) local areas prone to light variation (e.g. sunlight) that makes infeasible the use of image-based tracking approaches; and (3) the combination of the previous two conditions, demanding the use of hybrid tracking techniques invariant to light conditions and simultaneously capable of mapping issues related with terrain morphology and texture. Thereby, the experience manager may freely decide which is the most suitable tracking configuration to face a certain set of environmental conditions and the required resources to produce tracking assets rather than being concerned with implementation details. One must consider the trade-off the work required for setting a tracking configuration and its effectiveness. Ancient virtual buildings' hypotheses used to superimpose real-world ruins are procedurally produced by a third party that aims to streamline the creation contents (Adão, Magalhães, & Peres, 2016). MixAR also has a server-side software based in web services responsible for managing data related with tracking configurations and the respective augmentation models between the server and the mobile units. The whole system is developed upon previous work (Narciso et al., 2015).

An evaluation regarding usability (including presence, immersion, satisfaction, comfort and sickness) was carried out nearby the Vila Velha Museum (Vila Real, Portugal) with several participants. Most of them showed enthusiasm during and after these experiences, which seemed to increase their interest about virtual visitations in the context of cultural heritage. Results seem to validate the proposed enhanced version of the MixAR project when considering visitors' comfort, satisfaction and presence/immersion in the archaeological site.

In what concerns the paper's organization, the following section addresses digital applications on cultural heritage domain with stronger emphasis in AR/MR, along with the most important tracking techniques and associated issues. Section 3 focuses the MixAR system specification by presenting its overall architecture and its main components - including the geographical information system (GIS) server and user's mobile unit – from a conceptual viewpoint. Technical decisions are justified in Section 4, followed by implementation details and guidelines on how to set up an MR experience and some considerations towards MixAR system usage under the visitor's (mobile application) perspective, addressed in Section 5. In Section 6, the visitors' evaluation results to the proposed MixAR system are presented and discussed. Some conclusions, final remarks and future research directions are presented in Section 7.

2 RELATED WORK

Solutions ranging within the VC of Milgram and Kishino (1994) have been proposed for cultural heritage with the goals of promoting public's participation and improving knowledge transmission about work developed by both professionals and enthusiasts of archaeology, history and related areas. Technology has also been used as a tool to enable those professionals and enthusiasts in carrying out their tasks. In what concerns VR, many of the works found in literature focus museum-related solutions (Carrozzino & Bergamasco, 2010; Bruno et al., 2010), virtual museums for research dissemination (Robles-Ortega, Feito, Jiménez, & Segura, 2012), ambience/storyboard recreation (Rua & Alvito, 2011), heritage reconstruction and interactive experiences (Gaugne, Barreau, Le Cloirec, & Gouranton, 2013), as well as serious games (SG) applications (Mortara et al., 2014;Bustillo, Alaguero, Miguel, Saiz, & Iglesias, 2015; Jiménez Fernández-Palacios, Morabito, & Remondino, 2016; Kiourt, Koutsoudis, & Pavlidis, 2016; Rubino, Barberis, Xhembulla, & Malnati, 2015).

Other works gave primacy to the presentation of virtual contents placed upon real POI to provide archaeological sites' visitors with improved experiences under AR/MR environments. For example, Vlahakis et al. (2002) and Dähne (2002) have developed ARCHEOGUIDE: an AR system to visualize virtual reconstructions and historical information within archaeological sites composed of ancient buildings' ruins. Both GPS and image-based tracking were used to augment the 3D models nearer the visitor. Also addressing *in situ* virtual augmentation for cultural heritage, others (Miles et al., 2016) were able to achieve tracking using positional coordinates and orientation. However, relying in such approach for orienting and placing 3D virtual models is likely to result in lack of accuracy and in flickering. A "magic glass" for time travelling - a mobile AR application – is another proposal implemented by Bellini et al. (2013), which allows the visitor to know how certain places - denoted as glimpses of interest - looked like in the past, through image overlapping. The "time compass" of Fiore et al. (2014), followed a similar strategy, shortly after. Meanwhile, Ikeuchi (2013) presented an overview of his own experience in e-Heritage - author's designation for the area that deals with cultural heritage digitalization. Amongst other projects that involve geometric modelling and photogrammetry, the author also addresses MR, photometric consistency through shadows' processing, augmentation of computer generated images and an immersive tram visitation. In the latter, the visitor navigates inside a big CAD model augmented with image tracking, while a 3D movie displays some noteworthy historical events. While, in the same year, Han et al. (2013) focused on the use of image-based tracking techniques to augment virtual models in archaeological sites similarly to ARCHEOGUIDE, more recently, Duguleana et al. (2016) opted for using (1) GPS to present location-based markers signaling POIs; and (2) a hybrid tracking approach, combining a 3D map and image's features to augment both textual information and videos. Although 3D models are referred to as a possibility to complement the real world, apparently none is used in the proposed system. On the other hand, REENACT (Blanco-Fernández et al., 2014) was more concerned with the pedagogical potential behind the use of AR technology. It is a multi-stage role playing system that aims to improve learnability by involving users in historical battles through AR visualization for further analysis and debates. Within the usability scope, a wearable AR system was proposed with the aim of providing visitors with suitable experiences within a cultural heritage context (Brancati et al., 2015). Also, Pedersen et al. (2017) proposed TombSeer that is an AR holographic system with interactivity designed for museums that augments virtual information based on plaques or display cards tracking. Zhou et al. (2016) addressed the enhancement of history subject learning using an educational software for ancient environment simulation. Despite VR and 3D printed models visualization modes, an AR application was developed to allow virtual models augmentation directly upon textbook visual references. Meanwhile, a multidisciplinary approach that applies geographic information technologies to cultural heritage has been proposed by Marques et al. (2017) who aimed to provide tools for patrimonial valuation through digital representations. Other recent contributions focusing the acceptance of AR for cultural heritage tourism have been provided, considering the following aspects: the influence of user's cultural traits and applications' aesthetic and hedonic characteristics (Jung, Lee, Chung, & Dieck, 2018), as well as the importance of certain dimensions such as information quality and systems' cost of use (Dieck & Jung, 2018). With the goal of actively promoting the involvement of society in cultural heritage activities, Lim, Frangakis, Tanco, & Picinali (2018) proposed a Pluggable Social Platform for Heritage Awareness and Participation (PLUGGY) with AR and geolocation capabilities, whose contents can be managed through a curatorial tool and experienced using an application for augmenting data such as virtual models, text and live video streams.

Regarding the core processes supporting several of the aforementioned applications, an extensive AR survey (Billinghurst, Clark, & Lee, 2015) addressing tracking techniques to trigger contents' augmentation in AR/MR contexts establishes a classification in five groups. Magnetic tracking refers to the devices that determine pose out of magnetic field polarization and orientation measurements. Vision-based tracking is defined as an approach to detect pose through optical sensors that, in turn, can fit in one of the following three categories: infrared (e.g. using light emitting diodes, LEDs), visible light (e.g. through fiducial tags or CAD models) and 3D structure (spatial in-depth feature estimation). Tracking relying in accelerometers, gyroscopes and magnetometers is in another group known as inertial tracking. GPS tracking is also addressed as a particular category, exclusive for outdoor environments. Finally, to increase degrees of freedom, to enhance the accuracy of the individual sensors, or to overcome weaknesses of certain tracking methods, hybrid tracking systems that fuse data from multiple sensors are available.

In (Magalhaes et al., 2014; Narciso et al., 2015) tracking techniques are summed up in three main groups, but not in a contradictory sense: sensor-based, vision-based and hybrid. Sensor-based techniques can rely on a variety of trackers, such as GPS, mechanical, magnetic, ultrasonic and inertial (Narciso et al., 2015). However, they commonly present issues with tracking accuracy and/or the need to alter the real world by placing devices, which can be considered invasive to the physical context. On the other hand, vision-based tracking techniques can be precise. They follow one of two approaches: marker-based (e.g. Bajura & Neumann, 1995; Cho & Neumann, 1998; Kato & Billinghurst, 1999) or markerless (e.g. Koller, Daniilidis, & Nagel, 1993; Lourakis & Argyros, 2005). The former uses fiducial markers placed on the physical context, which makes it unsuitable for archaeological sites. Images are also supported, but they are not advisable in situations prone to light variation due to its influence on feature detection. In contrast, markerless approaches use existing features of the physical context. These approaches can be further divided into two main types: model-based and Structure from Motion (SFM) based (Teichrieb et al., 2007). While model-based techniques (e.g. Marchand, Bouthemy, & Chaumette, 2001) require information about the real world prior to tracking (Lima, Simoes, Figueiredo, & Kelner, 2010), such as a 3D model that is later used to calculate the camera pose, SFM-based techniques (e.g. Davison, Reid, Molton, & Stasse, 2007) do not require 3D information prior to tracking, which enables the augmentation of unknown physical contexts (Lepetit, Fua, & others, 2005). However, there is no control over where the augmentation occurs, which renders this type of markerless approach impractical in some systems. Lastly, hybrid approaches combine more than one tracking technique to compensate individual weaknesses and to combine their strengths (Azuma, 1997), also in accordance with Billinghurst et al. (2015). Systems based on hybrid approaches started to be commercialized during the 1990's and used mainly sensor-based techniques for orientation and position tracking (van Krevelen & Poelman, 2010). Eventually, as image-based tracking techniques became more robust they were also combined with sensor-based techniques (e.g. Porzi, Ricci, Ciarfuglia, & Zanin, 2012; Vlahakis et al., 2002) as well as with other image-based techniques (e.g. Pressigout & Marchand, 2006; Vacchetti, Lepetit, & Fua, 2004).

Even so, the inconstant environmental conditions that can affect part of the technique are likely to result in performance degradation. In some situations, the application of such hybrid techniques needs to be reconsidered, especially when low profile devices (mobile, with hardware capabilities constraints and cheap) are at stake, since the lack of processing power and/or sensors might lead to usage issues and/or unpredictable failures. Overall, it seems safe to state that in cultural heritage there is a significant need of AR/MR systems capable of making use of as many tracking techniques as possible, as a mean of improving their flexibility by simultaneously suppressing the lack of options for each condition set. Thereby, the MixAR system - which has been enhanced from (Narciso et al., 2015) to support multi-tracking - is presented in this paper to suppress these issues. It also represents an alternative to most of the existing AR/MR solutions, as it relies on cost-effective and light-weighted devices. Finally, a procedural modelling-based process that speeds up the generation of virtual buildings' hypothesis is also detailed.

Currently, many technologies and platforms for AR/MR development are available and still growing, showing that real-time tracking applications for augmenting information after the registration of camera and target of interest continues to be a subject undergoing intense study. For instance, Microsoft's Hololens (Microsoft, New Mexico, United States of America or USA) consists in a MR head-mounted display (HMD) with interaction capabilities that allows real-time 3D tracking. Besides inertial measurement units (IMUs) and depth cameras, there is a high-performance holographic processing unit (HPU) for handling the most demanding tasks such as spatial mapping and multimodal input recognition (e.g. speech and gesture). In spite all of its features, Hololens HMD represents an additional device the user must wear, at a significantly cost: 3000 USD for development purposes and 5000 USD for commercialization (Microsoft, New Mexico, United States of America or USA). More affordable are the Tango (Google, California, USA) technology-based devices (e.g. Lenovo Phab2 Pro and Asus Zenfone AR) which are capable of mapping and continuously tracking the environment, independently of being used indoors or outdoors. This is an accurate and extensible but, also, a demanding feature that requires good hardware – namely, central and graphics processing capabilities - to reduce lag effect in experiences, which might contribute for the reason why the minimal price found for Tango-capable smartphones is over 480€. Besides, considering that only a few of devices come with that specific depth sensor installed by the manufacturer, Tango is still far from deserving the title of mainstream technology that, in turn, might hamper the dissemination of cultural heritage applications aiming to promote public participation, as it is the case of MixAR. Thus, to ensure that applications reach the maximum target audience, they need to be developed for persons' daily devices, namely regular smartphones. To that end, the proper way to address an AR application development is through software development kits (SDK), suitable to implement requirement-oriented solutions with acceptable performances for the majority of the average smartphones, say, up to 250€. For example, BQ Aquaris E5 FHD showed to be capable of reaching around 20 frames per second during successful tracking occurrences (Pádua, Adão, et al., 2015) that are characterized by a demanding state in terms of processing since the smartphone must be able of showing an augmented virtual model while it keeps checking camera registration with the real-world target of interest . Currently, most of the SDKs relying in a free development paradigm - such as Wikitude (Salzburg, Austria), Vuforia (Parametric Technology Corporation, Massachusetts, United States of America) and Kudan (Bristol, United Kingdom) - are capable of targeting multi-platform and providing mature 2D tracking. Although, due to the need of using robust and stable markerless approaches to prevent markers invasiveness - especially when sensitive cultural heritage interdict to the public contact is a concern - and, also, to avoid constant photographic surveys adapting combinations of environmental variations - typical on outdoor environments - 3D tracking started to be developed and merged with sensor-based approaches. Wikitude implements this feature with a single approach named object identification. Kudan and Vuforia provide very limited versions of 3D tracking: the former relies exclusively in simultaneous localization and mapping (SLAM) while the latter only supports a confined range of geometrical entities. Another issue of the referred tools lies in the fact that most of them recommend to use their own web-based platforms to manage tracking assets. Apparently, Kudan does not require it. The ceased multi-platform Metaio SDK (Metaio GmbH, Munich, Germany) allowed having the best of both worlds: a wide set of robust 2D and 3D tracking approaches and tracking assets offline management. Meanwhile, Apple (Apple Inc., California, USA) has acquired Metaio Company (Metaio GmbH, Munich, Germany) – resulting in its SDK discontinuation – and, shortly after this event, the powerful ARKit (Apple Inc., California, USA) became available for Apple devices, exclusively. Notwithstanding, recent developments have endowing EasyAR

(VisionStar Information Technology (Shanghai) Co. Ltd., Shanghai, China) with features that are similar to the ones that could be found in Metaio SDK.
In the following section, MixAR specification is presented, providing more detail about the technical options taken for the multi-tracking system development.

3 MixAR Specification

The MixAR system follows a typical client-server architecture. Its main components are detailed in this section. Whilst the server stores MR experiences' configurations and provides a GIS module to manage the geographic area where visitations occur, the client-side consists in MARS devices responsible for managing the visitor's MR experience, with support for multiple tracking techniques.

3.1 General architecture

The architecture proposed in (Magalhaes et al., 2014; Narciso et al., 2015) for the MixAR system will be briefly presented in this subsection. It is comprised of three main components: (1) a mobile unit responsible for providing and managing visitors' MR experience (some lightweight and cost-effective proposals were addressed on Pádua, Adão, et al., 2015; Pádua, Narciso, et al., 2015); (2) a remote server in charge of managing and delivering relevant data to mobile units; and (3) a network infrastructure to enable communication between the remote server and the mobile units.
MixAR server-side is composed by a GIS module and a repository. The latter is used to store and retrieve virtual models and configurations to be provided to the mobile units. The former provides a way of georeferencing the area in which the MR experience takes place. Moreover, it is also able to define different levels-of-detail (LOD) that aim to provide a better management of computational resources, by exhibiting or hiding virtual models' chunks based on the distance between visitors and POIs. Each LOD definition is stored in a database, which is queried to build the configuration set to be transferred to the mobile units, along with the virtual models (Narciso et al., 2015). Fig. 1 depicts the server-side architecture, with its main components.

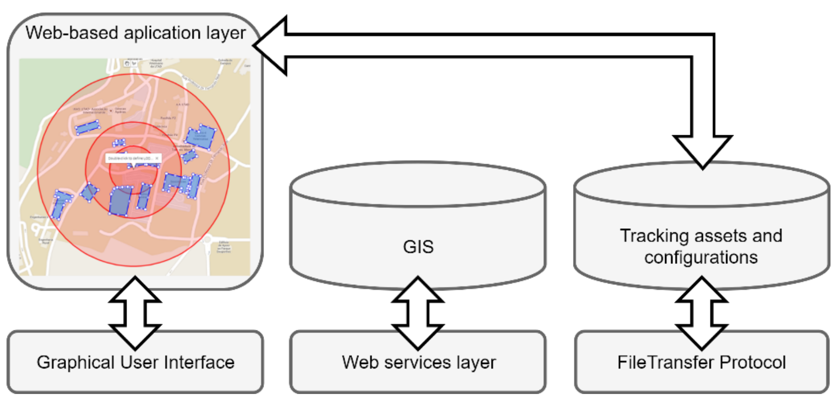


Fig. 1. MixAR system server-side architecture featuring a web-based GIS and its respective graphical user interface, a GIS repository, a repository of tracking configurations and assets and also the interface layers (web services and file transfer protocol).

According to Magalhaes et al. (2014), MARS are AR mobile units composed of three main components: visualization, context and processing. To keep them autonomous, a power supply is also integrated, whereas connectivity is ensured through the network interfaces. MARS were further detailed by Pádua et al., (2015). While the visualization component goal is the real-time presentation of virtual contents embedded in the real world, the context component is responsible for capturing contextual real world information, such as orientation and positioning. Therefore, it consists of three elements: location sensors, which provide the visitor's current position; inertial sensors, to determine the visitor's orientation; and optical sensors, for real world image-based acquisition. Finally, the processing component is responsible for: (1) gathering data acquired by the contextual element and through the network interfaces; and (2) processing it, specifically to tracking purposes. Processed data is then forwarded to the visualization component, so that visitors can see virtual content augmented upon the real world. Moreover, the processing component also obtains data from the server-side, through the available networks interfaces. Fig. 2 represents the MARS architecture, with its main components.

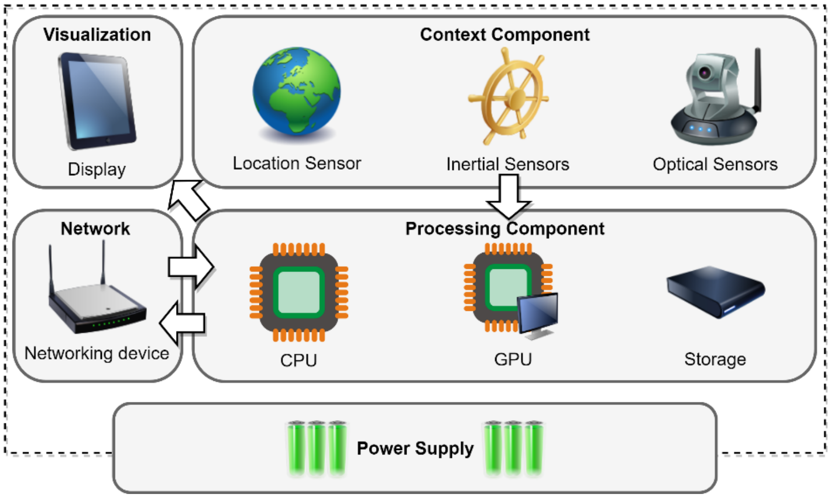


Fig. 2. - MixAR mobile unit architecture composed of three main components: visualization, context and processing. A power source and network interfaces also integrate the proposed architecture, as originally presented in Padua et al. (2015).

3.2 MARS device multi-tracking support

In what regards MARS's tracking operations, the work presented in (Narciso et al., 2015) supports only an hybrid tracking approach based on CAD models, which has raised the following issues: (1) cultural heritage sites can be composed of severely damaged or completely destroyed structures, which makes the edges extraction task for CAD model-based tracking very costly; and (2) switching tracking to a marker-based approach - by using damaged or destroyed structures' photographs - can be unsuitable for outdoor contexts, inasmuch as visual markers identification can be affected by light variations.

To overcome these issues, the algorithm that manages MR experiences on MARS devices was enhanced to support several tracking approaches, specifically one per visitation spot. Supported approaches are: marker-based, although this might not be the best option for cultural heritage if the technique that is being applied requires transformations to the environment, for example, through the placement of fiducial tags; markerless, namely natural features, 3D map and CAD-based model tracking.

At runtime, two element types are considered to properly perform (accurate) tracking activities: tracking configurations and its respective assets (e.g. tracking images, edges and augmentation models). The former specifies the tracking approach to be used (e.g. based on markers, images or 3D models) and its respective parameters (e.g. the initial pose camera position and its rotation). In turn, the latter consists on the use of three asset types:

- matching model: refers to the virtual structure(s) that is (are) used for comparison and matching with a real-world target (e.g. tags, images, 3D line models, point clouds, etc.);
- visual aid element: displayable and, sometimes, interactive elements that provide visual insights to the users about the real-world target that is being scanned by the tracking process, as well as the correct orientation that should be given to the device in use for a successful registration between the matching model and the respective target;
- virtual augmentation model: a transversal requirement that is displayed accurately aligned upon POI's are after tracking detection (i.e., successful correspondence between target and matching model).

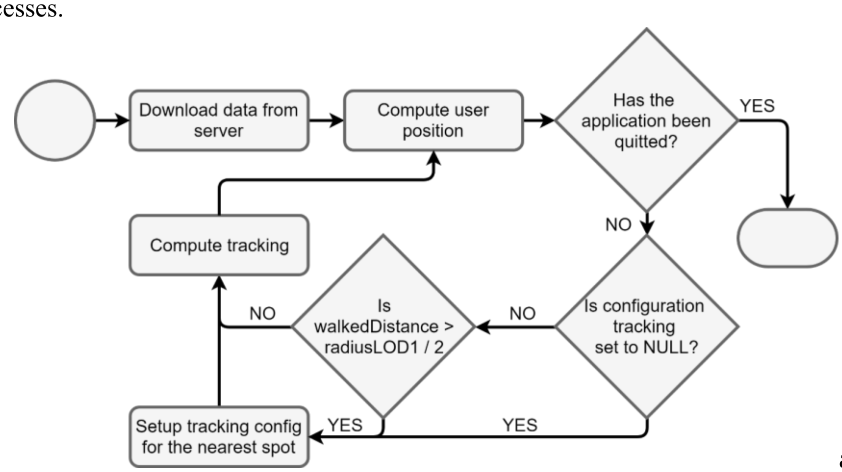
When using a marker-based approach, a tracking target's image - such as synthetized pattern (e.g. logo) or a fiducial tag - is needed as matching model. The very same targets can be used as visual aid elements. Concerning markerless approaches, three techniques are considered: CAD-model, 3D point cloud and natural features. In CAD model-based approach, a set of edges representing a real-world entity' contours (the tracking target) must be provided as a matching line model, which can optionally be complemented with a surface model. A tube model - a pipe-like structure that results from line model extrusion operation - can be used in this technique as visual aid. Alternatively, tracking based on 3D map consists in using pre-acquired 3D point cloud - stored as matching model - for comparison purposes with the real scene. Due to the abstract nature of the feature points, an image of the target of interest should be provided as visual aid while using 3D map tracking technique. Lastly, the natural feature tracking requires a picture - place of interest digital photography - representing the tracking target as matching model for further feature comparison between the stored image and the scene that is being captured by camera sensor. Table 1 sums up the use of matching models and visual elements by tracking technique. Regarding virtual augmentation models, they are displayed as result of positive correspondences between reality and virtual matching models, regardless of the tracking technique in use.

Table 1 - Matching models and visual aid elements used by tracking technique.

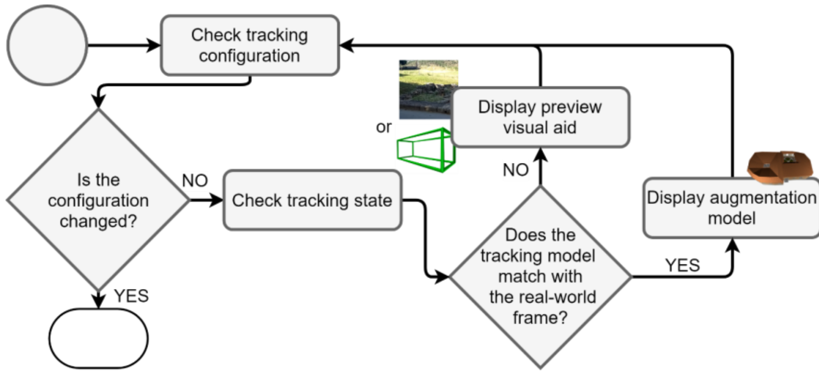
Assets / Technique		**Matching Model**	**Visual Aid**
Marker-based	Fiducial Tag	Tag features	Fiducial tag
	Image model	Image features	Image model
Markerless	3D map	3D point cloud	Image
	CAD-Based	Line (and/or surface) model	Tube model (line model-based)
	Picture	Natural features	Picture

After being produced (see section 4.2 for a quick description), tracking assets are submitted to the MixAR's server GIS module, which is responsible for their transfer - along with the MR experience configuration regarding georeferenced spots for visitation - to the visitor's MARS device.

A given MR experience starts by having the nearest visitation spot' tracking configuration prepared, based on the files provided by the server. During the archaeological site visit, the tracking configurations are switched by the MARS device, based upon the visitor's location and considering the tracking approach specified in the visit setup process. In Fig. 3, a couple of flow charts depicts the MARS device tracking configuration update and setup processes.



a)



b)

Fig. 3. MixAR's algorithm that manages MR experiences on MARS devices. While a) presents the tracking configuration update that is carried out while the visitor is moving within the archaeological site (adapted from Narciso et al., 2015)), b) depicts the tasks performed every time the tracking configuration changes. Whenever the tracking state indicates success, an augmentation model is displayed accurately aligned upon the tracking target. Otherwise, a preview asset (visual aid) that invites the user to look for a target and properly align the camera with it is shown. In the case of CAD model-based approach, a tube model (based on line model) representing the silhouette of a real world structure shows up in the display component, overlapped with the captured scene of the real world. For both 3D map and natural feature tracking techniques, a thumbnail of the real-world space is presented. Finally, the marker-based approach preview asset consists of a fiducial tag or image model that has, of course, to be placed somewhere in the real site.

MixAR's specification constitutes itself as an essential guideline for the overall system's implementation. Both MixAR's implementation and the process for setting up MR experiences will be presented in the next section.

4 TECHNICAL SPECIFICATIONS

To specify technical-related features aiming to support MixAR's implementation, technological surveys, respective analysis and several meetings involving UTAD-GEMA partnership were carried out, mostly at the project's start-up. Such specification guides server-side and mobile client-side development, regarding concrete supporting tools, platforms and technology-dependent aspects.

4.1 Server-side

MR experiences must be stored in a remote server, which provides the needed tracking dataset whenever demanded by mobile client-side, as it was already explained in the previous section. In this way, a dynamic management of MR experiences is ensured, by isolating tracking related data from application logic. Considering such requirement, partnership entities agreed in adopting an Unix-based server with open-source resources such as PHP and MySQL capabilities, by a rental contract for a period matching project's duration with a third party company. To implement the GIS application for MR experiences' spatial managing, the popular Google Maps JavaScript application programming interface (API) - owned by Google (California, United States) - was the selected option. Thereby, a cost-effective server-side can be integrated to balance the investment needed for mobile client-side.

4.2 Mobile client-side

Specifically concerned with the MixAR's client-side development, several SDKs for AR/MR were surveyed in terms of pricing and features: the ones that, at least, allowed a free development without having to buy a license for gaining access to interesting core features such as multi-platform targeting, 2D and 3D tracking were preferred. UTAD and GEMA opted by adopting Metaio's SDK, which was a very complete AR programming solution comparatively to direct competitors. Besides free license for development, Metaio's SDK also offered much more 2D and 3D tracking techniques than other similar tools, as well as it supported multi-platform

deployment. Unlike most of AR SDKs, the one proposed by Metaio also allowed to manage tracking assets without the need of declaring them in proprietary web-based platforms, which could compromise eventual plans for developing a semi-automatic framework capable of handling tracking assets' production and upload to MixAR server-side. Regarding multi-platform deployment, it could be achieved through a package specifically developed for Unity 3D (Unity Technologies, San Francisco, USA), which was the reason behind the selection of such development environment. Notwithstanding, Unity 3D has its own rendering engine - capable of handling content presentation considering different screen sizes and resolutions - and enables free development with functionality restriction.
The fast pace that characterizes AR-related technology development ended up resulting in Metaio's acquisition by Apple Company. Nonetheless, while existing SDKs extended their features - for example, Vuforia, which only offered 2D tracking, has recently developed 3D tracking techniques - alternative SDKs similar to Metaio - e.g. EasyAR - have emerged. This means that in spite of Metaio's SDK discontinuity, other modern tools can be promising for replicating the process underlying the proposed MixAR system.
Next section will focus the MixAR's implementation, as well as its well-defined process for setting up MR experiences.

5 System's Implementation And MR Experiences' Setup

This section presents the MixAR system's implementation – both server and client-side applications – based on the proposed specification. Moreover, the process by which MR experiences are set up is also described.

5.1 MixAR system Implementation

Server-side GIS module was implemented as a web-based application, using the Google Maps Javascript API that allows to mark and manage geographic areas for MR experiences. Some of its main supported operations are: (1) polygon delimitation and POIs adjustment, upon the geographical area where the MR experience (the visit) will take place; (2) definition of LOD rings for detail management regarding the virtual buildings that will be loaded at the client side; and (3) export of GIS data in metrical units, based on geographical bounding boxes and by converting relative distances - involving latitude/longitude coordinates - to meters (GeoDataSource, 2017). The latter retrieves terrain virtual models for further use in the process that handles MR experiences' setup, addressed later on this section.
Regarding communication with the MARS devices, three web-services are provided (Narciso et al., 2015):

- Get last update date: this web-service enables to determine if a mobile unit has both the most recent tracking configurations and assets. Otherwise, they are obtained from the MixAR's server and overwrite the existing ones.
- Get the nearest building for tracking: presented in Fig. 3 a), this web-service is invoked every time the visitor walks a distance above half the minimum LOD radius. It identifies the building that should be prepared for tracking, considering the visitor's position.
- Get buildings per LOD: this web-service returns a list of buildings (segmented by LOD) located in the surroundings of the visitor's position. The list is then used by the MARS devices to load virtual buildings with the proper detail. This web-service is implemented but it is not being fully explored, since only two LODs are addressed, for the time being.

As for MARS devices' physical implementation, some wearables compliant with the proposed architecture were selected and tested by Pádua et al. (2015a, 2015b) as lightweight and cost-effective solutions for providing immersive and non-immersive experiences, in cultural heritage context: tablets (Samsung Galaxy Tab Pro 8.4 – Android and an Asus Vivo Smart ME400C – MS Windows), a smartphone (BQ Aquaris E5 FHD), a laptop (Toshiba P750-103), a single-board computer (Eurotech Antares core-i7) and head-mounted displays (Vuzix 1200DXAR and the NEJE Colorcross Box + BQ Aquaris E5 FHD set).

MixAR's MARS devices' application was developed using Unity 3D: a powerful game engine with a proprietary renderer, suitable for multi-platform deployment. Metaio's SDK for Unity3D was integrated to ensure the required MR capabilities for MixAR. This SDK operates by separating the tracking algorithms from the tracking configuration files, which leveraged the implementation of enhanced features for MixAR's MARS devices' application, more specifically the multi-tracking capabilities. To properly perform tracking activities at runtime, Metaio's SDK requires the following elements for each tracking approach incorporated in a single MR experience: (1) a XML file properly configured with the desired tracking approach (based on e.g. markers, image, 3D model) and a few parameters, such as the initial camera pose position and rotation; and (2) assets to inform the visitor about the tracking target (pictures, markers or visual aid elements), as well as augmentation models representing ancient structures. The tracking elements production process is detailed in the following subsection. After being produced, they are submitted to the MixAR's server GIS module. Afterwards, they are transferred to the MARS devices, along with the MR experience configuration (georeferenced spots for visitation), when the mobile application is booting up and the MR experience configuration is missing or is outdated.
The following iterations of MixAR's MARS devices' application are carried out according with the presented specification:

- the tracking configuration of the visitor's nearest POI is loaded;
- visual-aid assets are shown accordingly with the loaded tracking configuration, to inform the visitor to which tracking target (e.g. a ruin) the MARS device camera should be pointed;
- virtual reconstructions are augmented in the real-world whenever a successful tracking occurs;
- finally, the visitor's position is continuously monitored to check if walked distance is superior to half of the minimum defined LOD and to properly change the tracking configuration whenever the nearest building status changes.

As it was already pointed out in (Narciso et al., 2015), the blend between AR and VR occurs smoothly, as long as the tracking technique in use supports the continuous capture of features surrounding the target of interest, during successful tracking registrations. In a typical use case scenario involving MixAR and right after camera registration in a target of interest, a virtual building is augmented in front of the user, who initially stands in the outside of it experiencing an AR approach. Meanwhile, surrounding features are collected from camera imagery to build a complementary 3D map that helps to strengthen virtual building tracking robustness. This allows the user to walk towards the virtual building, while VR gets progressively over AR in a transition process that reaches consolidation when the user is completely immersed inside the virtual building. This augmentation model remains up until the occurrence of a substantial camera sight loss over both extended map and tracking target POI's area.

An "extended environment" feature is also available. It uses positional tracking to present a preview of the augmentation models with the lowest LOD floating around the area in visitation, with the exception of the nearest active POI. As such, the visitor is provided with an insight about the surrounding spots that can be visited. Inertial sensors from MARS device' context component are used to stabilize those preview models in their respective real-world positions (compensation made through pitch, roll and yaw readings).

5.2 Process for setting up MR experiences

Virtual contents production towards MR experiences preparation and configuration is done through an offline process, whose first task consists in generating virtual models through a procedural modelling tool. Then, the tracking elements - that include visual aid and augmentation models - are created/edited using a 3D modelling software - in our experiments we used Blender (Blender Foundation, Amsterdam, Netherlands) that is open-source - and exported with the right scale, position and rotation to be included in the configuration files. The latter are parametrised with relevant data regarding tracking specifications. Lastly, all files are uploaded to the

MixAR's server and become available for on-demand transferences to MARS devices. Fig. 4 presents the overall process to prepare and configure MR experiences.

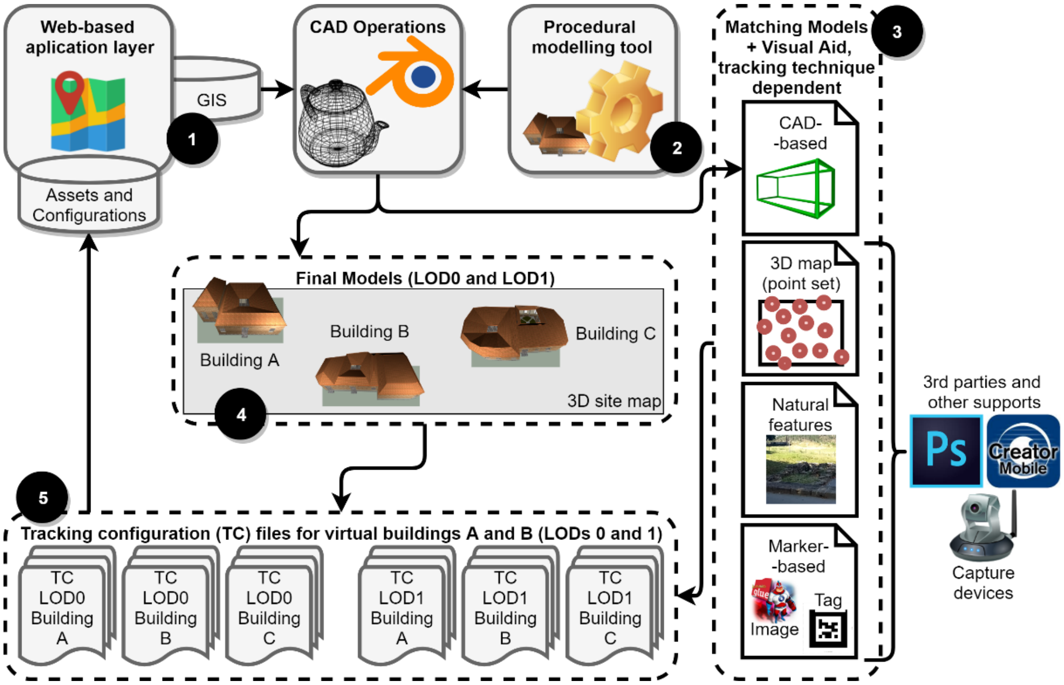


Fig. 4. Process for setting up a MixAR's MR experience: (1) upon request, the MixAR's server returns a cultural heritage site GIS virtual model; (2) virtual models representing ancient buildings hypothesis are generated in a procedural modelling tool (Adão et al., 2016); (3) matching models and visual aid elements must be produced depending on the tracking approach that is planned to be applied, more specifically, CAD-based tracking involves the production of line models and respective tube models through a CAD tool for visual aid; 3D map tracking relies on pre-acquired SfM-based point clouds - using, for example, Metaio Creator tool for that purpose or some similar software – that are used as matching model and, for visual orientation, a picture of the real-world space is a plausible resource; natural features - based on Scale-invariant feature transform (SIFT) or speeded up robust features (SURF) approaches, for example - and marker-based tracking uses pictures of the place of interest, fiducial tags and image markers as both matching models and visual aid elements; (4) a CAD tool is used to produce different LODs for the generated models, with a proper scale dimension and rotation, considering the GIS virtual model; (5) MR experience's configurations are then set up with the proper tracking approaches and respective assets (augmentation models + matching models + visual aid elements), to be finally uploaded to the server.

5.2.1 Exporting GIS-based flat map as 3D virtual model

Server-side GIS purpose is to create and store geographic references of cultural heritage sites, as it was previously addressed in section 3. Additionally, there is an on-demand mouse-click-based functionality that allows the 3D model exporting of the site map with the measuring units properly converted to the metric system. By using this functionality, the person preparing the AR experience is provided with flat topographic guidelines for further tasks related with positioning, rotation and scaling of the hypothetical virtual building reconstructions.

5.2.2 Using procedural modelling as a booster for content production

Procedural modelling is suitable to be used for testing hypothesis based on virtual models that enable theory formulations about missing or severely damaged ancient buildings. Commonly, the production of these models is expensive and time and resource consuming. Thereby, the ontology-based procedural modelling system proposed in (Adão et al., 2016) was used to mainstream the production of augmentation models, with the intent of integrating them in the AR experiences provided within the MixAR scope. It is important to highlight that this procedural modelling system is capable of producing virtual models of buildings with an ancient look, with particular relevance for MixAR, since those kind of virtual models are required for one of the main goals of this project, which is the in situ MR-based visualization of virtual reconstructions regarding severely damaged cultural heritage.

5.2.3 Producing assets and adjusting virtual models'

Depending on the requirements of the adopted tracking approach, markers (e.g. photographs) or real-world structures silhouette represented by virtual models of lines that can also include surfaces have to be produced. Examples of tracking elements for both marker-based and markerless approaches are illustrated in Fig. 5.

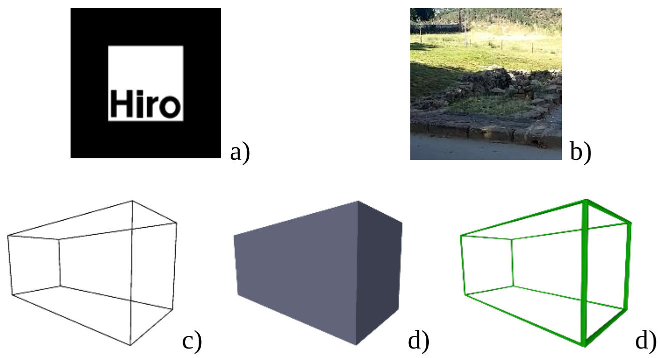


Fig. 5. Examples of assets: a) represents a fiducial tag; b) consists in a ruin picture (main asset for the image-based tracking approach); c) d) and e) depict a line and surface model for CAD-based tracking. c) is the line model for internal processing; d) represents a surface model and e) depicts the visual aid model for the user.

Regarding marker-based approaches, a picture or a fiducial marker would be enough as register for tracking, even when a hybrid approach combining 3D point clouds is planned to be used. This kind of registers are easy to produce and usually result in good approaches when the environment has a controllable source of light.
On the other hand, markerless approaches demand more work when it comes to set up the elements required for registering tracking. Here is an explanation of some of them:

- Line model (Fig. 5 a)): represents each structure contours and is used to find the correct camera pose through the alignment of the virtual edges with the real-world edges obtained from captured frames;
- Surface model (Fig. 5 b)): is usually optional, although it can be useful to a subset of markerless-based approaches, to determine the 3D location of projected feature points (SLAM) tracking as well as to detect the visible lines of the line model, based on self-occlusion;
- Visual aid model (Fig. 5 c)): aims to provide the visitor with visual orientation during the manual alignment of the implicit line model with the edges of the real-world structures. If a matching occurs, it triggers the augmentation of the real-world structure with proper virtual content.

The setup of markerless-based approaches involves some measurements of basic lines that must be manually surveyed and modelled as lines, accordingly with the ratio between the CAD units and meters. To ensure a better performance, the surface modelling step is ignored. The visual model is made up of the previous basic lines but with a thickening operation. These elements are built in isolated layers for exporting.
Besides producing assets that act as registers for tracking control, some adjustments must be accomplished so that the visualization of augmented models displayed by the mobile platform during successful tracking states can be correctly presented to the visitor (i.e. aligned with the ruins and with the proper size). At this stage, the virtual model representing the geographical area (building bases of ruins included) where the AR experience

will take place is already available and ready to be used as a spatial guideline for this virtual models' adjustment step.
Both virtual GIS model and buildings are imported to Blender software, also using the support feature for multiple layers. In there, the virtual buildings are moved, rotated and scaled to properly match with the GIS model building bases. The next step is to replicate those virtual buildings to other empty layers (one per building) for further operations towards the augmentation of virtual elements upon the real-world. Thereby, the replicated virtual buildings that keep the full level of detail (originally provided by the procedural modelling tool) are individually edited foreseeing a proper visualization in the mobile application. These editing tasks consist in repositioning them in the (0,0,0) point, maintaining both the rotation and scale that came from the original group of virtual models. With the proper scale and rotation, these models are ready to be replicated as many times as needed for empty layer sets to work the LODs.
Despite system's promptness to deal with several LODs, only two levels will be addressed in this explanation, for the sake of simplicity. LOD0 virtual models without interior rooms are the simplest ones and, consequently, the lighter regarding computational burden. They are suitable to be used in the extended environment visualization feature that intends to provide the visitor with gross information about the surrounding POIs or ruins that can be visited. On the other hand, LOD1 virtual models are kept with full detail to provide the most complete visualization to the visitor, during the tracking-based augmentation upon the nearest visitation point. After those operations regarding virtual models' LODs, both groups are exported, right before the creation of configuration files specifying the tracking features for each visitation point.

5.2.4 Setting up tracking configurations

Tracking configuration files have a very important role in the process because they tell Metaio SDK how to manage tracking for each visitation point by specifying the following information: (1) the tracking technique to be used; (2) the virtual models for augmentation; (3) markers/CAD-based tracking registers; (3) initial camera pose, i.e., the orientations (optional feature using quaternion vectors instead of rotating the models in the Blender editor) and distances that the visitor's camera should keep from the real-world structures to achieve successful tracking. Metaio website (Metaio, Munich, Bayern) provides a template – a file already filled with mandatory parameters and comments in each field regarding the possibilities - that can be used as a guide to setup tracking configurations more easily and quickly. Next subsection will address the distribution of those contents among the MixAR system components.

5.2.5 Uploading tracking for the server

After setting up both virtual contents and tracking configurations, they must be uploaded to the server that delivers them to the visitor's application (running on MARS), by request. Thus, a directory structure separating configurations and augmentation models was stablished in server-side. The tracking folder stores assets for tracking and Metaio-based configurations packed into zip files, while the augmentation models with different details must be placed in the respective LOD folders (LOD1, LOD2, …, LODN). By convention, the name of each zip file corresponds to each target visitation point ID (attributed during the GIS-based setup made using the server-side application). By complying with these conditions, the elements can be downloaded by the MARS, which demands updates whenever the server-side GIS configuration file date differs from the one previously downloaded to the client-side. Lastly, the MARS application algorithm that manages tracking is ready to perform.

It is noteworthy to highlight that the proposed MixAR system isolates tracking data from application logic. Thereby, a MR experience manager can orient its entire attention to the tracking assets production regarding points of interest within a specific archaeological site and considering environmental conditions (terrain morphology and texture, for instance), rather than being concerned with source code adjustments or any kind of implementation to adequate mobile application behaviour whenever the MR experience changes. Essentially, tracking configuration sets can be altered for adapting new MR experiences but the implementation that carries out location-based tracking assets switching along the visitation area remains the same.

5.3 Usage scenario from the visitor viewpoint

MixAR system execution has a well-defined sequence of steps that can also be explained under the visitor's perspective. For a given experience taking place in a specific archaeological site, MixAR mobile application (client-side) starts by presenting an idle window while it requests data to MixAR server-side: in the very first execution, tracking assets are immediately downloaded; in the subsequent ones, a download will depend on the availability of server-side updates.

When tasks related with update checking/download end, MixAR mobile application jumps to the experience manager main window wherein a few interactive graphical elements are displayed, more specifically: a 2D map showing visitor's position in the archaeological site; a couple of buttons, one for quitting the application and other for reloading tracking configuration from local storage (reset functionality created for testing purposes); and an extended environment that presents buildings floating in their respective (approximate) positions - rough location-based tracking - to improve user insight about the available POIs. According to visitor's position, the tracking configuration regarding the closest POI (e.g. ruin) is loaded and a corresponding visual aid element - based on image or 3D line model, depending on the loaded tracking approach - is shown. At the same time, the homologous virtual model floating in the extended environment is disabled, to avoid visual interferences with the loaded tracking configuration (otherwise, virtual elements belonging to rough and accurate tracking would overlap). Regarding the mentioned visual aid element, it intends to provide visitors with a visual hint, which can be seen as a preview indicating where and how to point MARS's camera to achieve successful registration with POI's area. Such registration triggers the augmentation of a virtual building that is seamlessly aligned with the respective POI's area, providing visitors with the freedom to explore that augmentation model that adapts both rotation and dimension according to the visitor's line-of-sight. The AR-VR transition occurs when the visitor walks towards a virtual building aiming to enter, which is possible if the tracking technique in use supports extended features mapping. Augmented virtual building and visual aid element switch between them according to the following occurrences: whenever a significant part of the POI's area gets out of camera sight, visual aid element is shown; on the other hand, if the camera has a good enough alignment to reach successful registration with the POI's area, augmentation virtual building model is presented.

While the visitor moves around an archaeological site, tracking configurations change respecting the previously explained visitor-POI proximity criterion. Switching process regarding visual aid/augmentation model presentation is transversally reapplied to each loaded configuration. This cycle ends when the visitor presses the quit button hanging in the application's graphical interface.

The next section will address tests made to evaluate the MixAR system regarding visitors' acceptance, specifically the comfort, satisfaction and presence/immersion.

6 MIXAR SYSTEM'S EVALUATION

To evaluate the MixAR system regarding visitors' acceptance, specifically comfort, satisfaction and presence/immersion, a set of tests were run. The tests took place in the vicinities of the Vila Velha's Museum (Vila Real, Portugal): an emblematic place surrounded by a chapel, the city gates' ruins and an open field with a painted wall (Fig. 6). Henceforth, these POIs will be identified as structures A, B and C, respectively.

Fig. 6. Aerial view of Vila Velha's Museum and of the surrounding POIs: a) chapel; b) city gates' ruins; and c) the open field with a painted wall. As these POIs are located outdoors, sunlight affects them differently.

To evaluate the visitors' comfort, satisfaction and presence/immersion with the prepared MR experience, participants answered to a given set of questionnaires (based on Jennett et al., 2008; Kaufmann & Dünser, 2007; T. Olsson & Salo, 2011; Thomas Olsson, Kärkkäinen, Lagerstam, & Ventä-Olkkonen, 2012; Witmer & Singer, 1998), which were also filled with their consent.

6.1 Materials and methods

Two MARS devices were used in the MixAR system's evaluation tests involving participants. Each provides a different immersion level: an immersive solution that combines a smartphone and VR glasses (BQ Aquaris E5 FHD + Neje Colorcross) and a non-immersive solution using an Android tablet (Samsung SM-T320), both depicted in Fig. 7 (left and right, respectively).

Fig. 7. MARS devices used in the MixAR system's evaluation tests with participants: on the left, a smartphone inside VR glasses (BQ Aquaris E5 FHD + Neje Colorcross), used as an immersive solution; on the right, the non-immersive solution using a Samsung SM-T320 tablet.

During the tests, resolutions were adapted in accordance with the used visualization mode. While a 640x480 resolution was used in the non-immersive tablet-based MARS, with a downsample of 2, the immersive smartphone-based MARS was set up with a 320x240 resolution without downsample, due to the use of binocular vision.

As aforementioned, MixAR's system supports several tracking techniques. However, in this particular test set only two were used. For structure A, a hybrid CAD model tracking technique was used, whilst for structures B and C, a Map 3D tracking technique was applied. Fig. 8 presents the MR experience process, with the virtual models, visitors' visual guidelines, tracking configurations and the scene's augmentation.

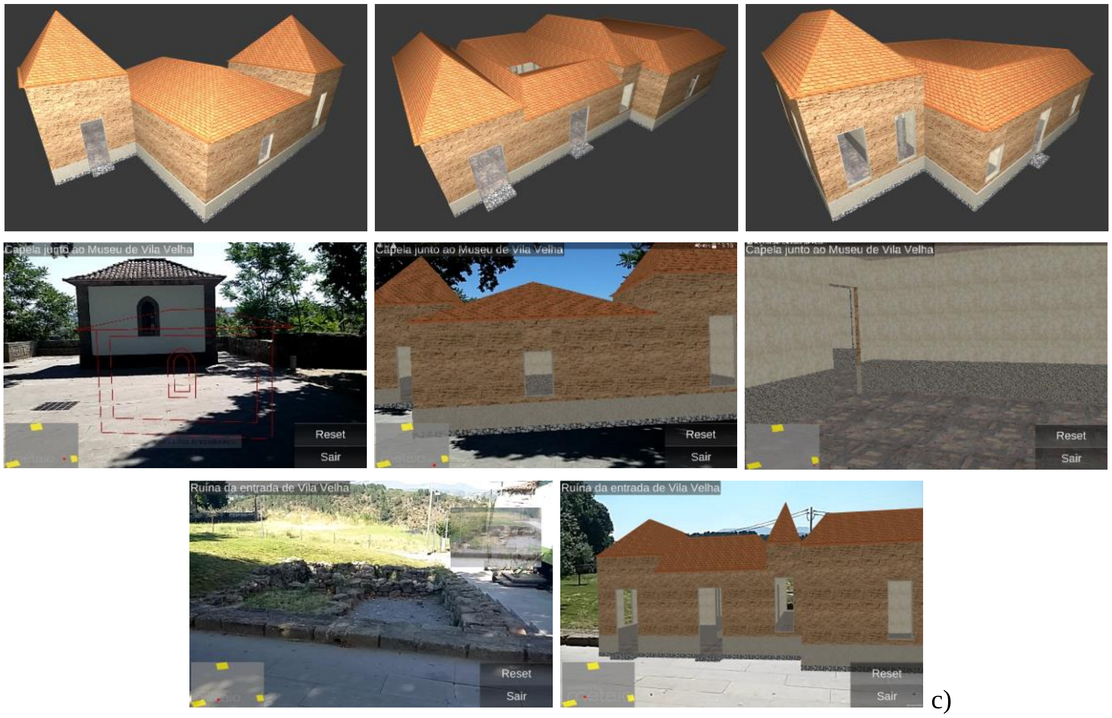


Fig. 8. Vila Velha's MR experience and related virtual assets. In a) the virtual buildings used for (post-tracking) augmentation are depicted. In b) a representation of the CAD-based tracking approach is depicted, where a line model is firstly presented to guide visitors in the alignment task (left image). After a successful overlap with the tracking target, the augmentation model shows up (centre image). The last image (right image) presents the visitor inside the building, which is kept visible unless a significant part of the tracking area stays outside the camera's sight. In c) there is a 3D map tracking setup in which several previously acquired feature points are used during the MR experience, as tracking references. An image is presented to the visitor - in the display's upper-right corner - showing the target to search (left image). Then, a virtual building is augmented in the image, after matching feature points (right image).

Structure A - the chapel - has a well preserved straightforward silhouette, which facilitates the edge extraction process by using a CAD software. Hence, a hybrid CAD-based model tracking approach was considered. Moreover, the referred tracking technique, known for both its robustness and accuracy, was applied with good results in previous work (Narciso et al., 2015). Regarding structures B and C (city gate ruins and open field with a painted wall, respectively), their morphology is not suitable for edge extraction in such a way that ensures both an acceptable precision and robustness. Thus, a 3D map tracking technique was chosen for both structures. This technique relies in a previously captured point cloud, stored as a model to control the tracking activities. Runtime comparisons between the camera's frames' point clouds and the stored model are made and matches above a given threshold (specified in the configuration) trigger the augmentation using a virtual model. Third-parties can be used to make surveys very quick and almost effortlessly (for example, before Metaio's acquisition by Apple, Metaio Toolbox was available to that end).

Regarding the set of tests, each participant was instructed to visit the POIs in the following order: structure A, then B and finally C. When using the immersive solution, participants were escorted by one of the authors, to prevent any incident. After finishing the MR experience, participants were asked to fill out a questionnaire, used to gather comfort, satisfaction and immersion data. A System Usability Scale (SUS)-like approach (Brooke, 1996) was used to proceed with the analysis of user satisfaction, presence and immersion questionnaires. A scale ranging from 0 to 4 was applied to rate the questions considering the ones with inverted positivity that were included to infer about visitors' attention and sobriety. Moreover, questions are scaled to a score ranging between 0 and 100 points providing a global tendency per participant and MARS. For comfort and sickness evaluation, two question sets aiming occurrences registration and counting (discomforts or side

effects) were employed. The questionnaire used for SUS-like approach evaluation is made available in Attachment A.
A total of 18 participants – 12 males and 6 females - took part in the MixAR system's evaluation tests. The majority, ≈56%, were students of technological areas, with experience in using mobile devices. Each MARS device was subjected to 18 tests, which results in a total of 36 completed experiences.

6.2 Results and discussion

Results for both immersive and non-immersive MARS show that they are appreciated in general, with a noticeable preference by the former solution.
Regarding user satisfaction, non-immersive MARS reached the higher rates of the entire SUS-based evaluation (77.53/100 score points) while the other one stayed more than 6 points below, also with a breaking record disparity comparatively to presence and immersion. Results in both MARS were boosted out by tendencies that include a general desire for having this kind of solutions on AR systems available on museums for interactive visitations and also by the overall empathy developed around the experience as well as a manifested will to repeat it. Questions related with virtual buildings visualization and stability lowered the overall score, perhaps due to a random, although, adverse combination of conditions characterized by lighting variation (presence/absence of clouds, period of the day and sun position, etc.) and factors intrinsic to the selected POIs' (irregular surfaces hard to map and track, poorness in texture elements enabling features extraction, among others). Additionally, adopted MARSs' limited computational capabilities and associated lag during experiences could had influenced the aforementioned overall score penalty.
The lower - still acceptable - scores were obtained in presence evaluation, where the immersive and non-immersive MARS reached 71.18 and 66.32 points, respectively. It turns out the devices that participants were carrying had a negative impact on the results as well as on visual quality and the lack of engagement. The forced 'artificiality' involved in the tracking process - which requires the user to align the device with the real-world target in a certain position and orientation - can justify the first issue. Reasons for the second issue might be related with the low screen resolutions that were set up to ensure a fair trade-off between the experience fluidity and the available computational results. Besides, the non-immersive MARS has a display prone to outdoor's light reflections which, in some conditions, might lead the visitor to additional vision efforts. Eventually, the conjunction of the first couple of identified issues constitutes the third's one core. Oppositely, some aspects dividing the users between concordance and indifference contributing to a balanced score include: the easiness to adapt to the experience, absence of confusion/disorientation feeling and the possibility of approaching virtual buildings for a better observation.
Immersion evaluation had encouraging results for both MARSs (75.64 and 72.76 points, respectively). It can also be observed the best overall score for the immersive one when compared to its homologues MARS in satisfaction and presence evaluation. Aspects related with participants' interest, curiosity, motivation and feeling of achievement were responsible for the good results that could not be higher due to a few identified issues: for example, some participants did not feel sufficiently involved in the experience to forget quotidian concerns, while part of them reported problems related with persuasion in virtual models presentation, as well as their engagement with the real-world.
The overall SUS results inferred from participants' satisfaction, presence and immersion evaluation on both immersive and non-immersive MARS are depicted in Fig. 9.

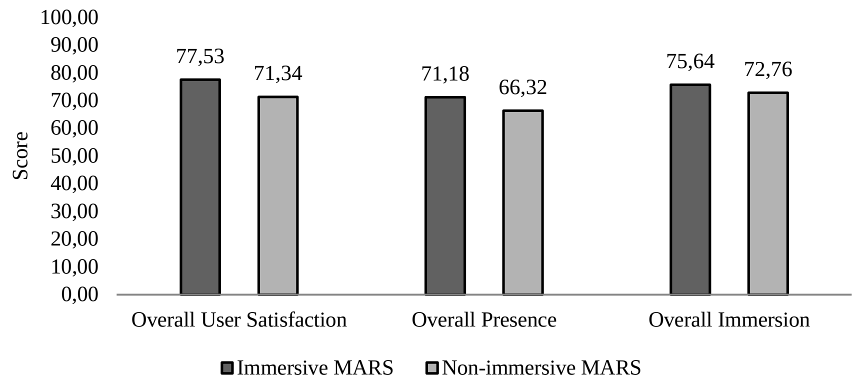


Fig. 9 – Overall SUS results for participants' satisfaction, presence and immersion, considering a sample of 18 individuals that tested both immersive and non-immersive MARS.

In what regards comfort evaluation, participants were asked about the tiredness or exhaustion they felt in specific body parts, during the MR experience. Results (Fig. 10) indicate 11 complaints about some kind of discomfort (not necessarily by 11 different users) – arms (6 occurrences), shoulders (2 occurrences) and general tiredness (1 occurrence) - mostly with the non-immersive MARS device. With respect to the immersive MARS device, there were only two discomfort complains: one for nasal dorsum and other for legs (must likely related with time spent standing).

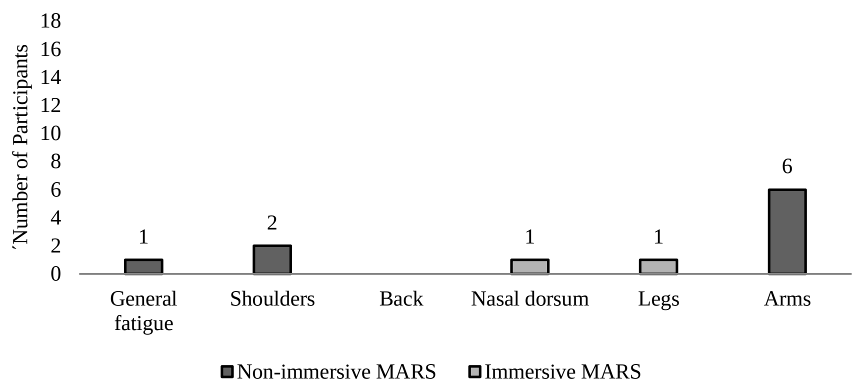


Fig. 10 - Body parts in which participants reported fatigue and exhaustion. The number at the top of the bars points out the quantity of participants that reported a problem in each case.

During the MR experience, around 5 complaints reporting some kind of discomfort related with the non-immersive MARS device use were registered, whilst the immersive solution had 6 complaints. Dizziness, tired eyes, sight focus, disorientation, blurred vision and concentration issues are among the reported problems. Unexpectedly, the number of participants experiencing disorientation was slightly higher in the tests made with the non-immersive MARS (Fig. 11).

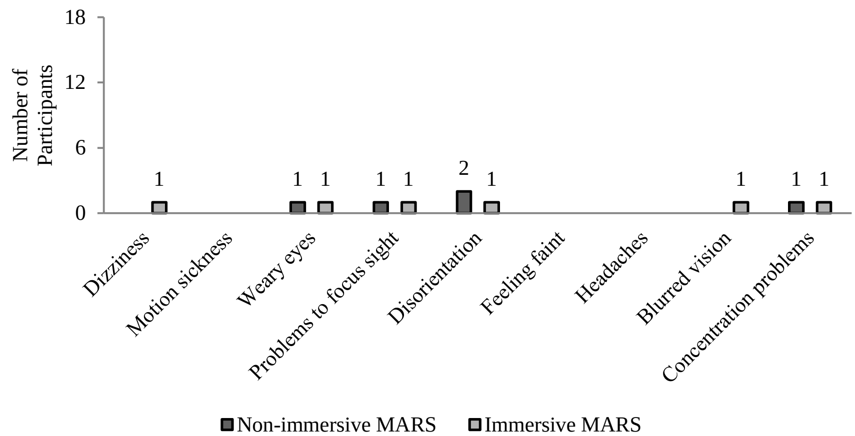


Fig. 11 – Discomforts reported by the MR experience participants. The number at the top of the bars points out the quantity of participants that reported the problem in each case.

Summing up, obtained results for satisfaction, presence and immersion seem to be quite acceptable. Only the SUS score obtained from the non-immersive MARS presence evaluation is below the desirable. According to participants' answers, it is fair to conclude that there was a general empathy by the experimental MR trial that earned positive feedback regarding easiness to adapt and movement freedom. Regarding issues related with virtual augmentation models' visualization and stability that were pointed out by the participants with impact in persuasion and real-world engagement, they are likely related with screen resolution and outdoor's illumination problems, which can be overcome by adopting more powerful devices to suppress the need of reducing resolution and by using mate screens instead of glossy screens. Moreover, before providing the final MR-based experience to visitors, experience managers are strongly encouraged to: (1) select the most adequate tracking approach for the desired environment, (2) fine tune its configuration parameters - to establish a balance between false positives and detection failures - and (3) perform corrective tests in the MR experiences that take place outdoors, whenever illumination conditions change significantly (indoors is not so critical since illumination sources are usually controllable or, at least, predictable). Comfort and sickness evaluation was also very satisfactory inasmuch as complaints were residual. Considering equation 1 metric:

$$\text{rate} = \frac{\text{number\_of\_ocurrances\_parameter\_x}}{\text{total\_of participants} * \text{total\_of\_parameters}} * 100 \quad (1)$$

non- and immersive MARS obtained, respectively, 8.3% and 1.85% of participations for comfort, while the results on sickness evaluation was of 3.09% for the non-immersive MARS and of 3.70% for the immersive one.

7 Final Remarks

MixAR is a MR system developed to provide visitations *in situ* to the past, allowing visitors to visualize hypothetical virtual reconstructions of buildings that no longer exist, while freely moving around the archaeological site. This system evolved from a single tracking-based version (Narciso et al., 2015) to the current one, supporting several marker and markerless tracking approaches, to provide the experience manager with freedom to: (1) select the most suitable approach to use at a given archaeological site and considering environmental conditions influencing that space and its elements (terrain/ruins morphology, textures, light etc.); and (2) choose the most adequate trade-off between technique robustness and required work/time to produce the assets. Table 2 presents a brief summary identifying the main differences between the preliminary (Narciso et al., 2015) and the enhanced MixAR versions.

Table 2 - Differences between MixAR's preliminary version (Narciso et al., 2015) and current version by tracking approach support, asset production requirements, environment applicability (outdoors/indoors) and visitor guidance capabilities.

Feature \ MixAR version	MixAR preliminary version (Narciso et al., 2015) vs.	MixAR enhanced version
Tracking approach	CAD-based.	2D recognition (fiducial tags/images), CAD-based, 3D point cloud and natural features.
Assets production	Burdensome, since it required systematic production of CAD-based assets, which - most of the times - involves measurement surveys in the field, CAD-based line model production and many adjustment operations over both visual aid and augmentation elements.	Provides flexibility for selecting less demanding tracking approaches regarding assets production, for example, based in simple photographs. Notwithstanding, it is up to the experience manager to decide when and where to use them.
Environment suitableness	Projected for outdoor environments with variable light conditions but also assuming the presence of discriminable edges in the ruins, which can be challenging to find.	Flexible for both indoor and outdoor environments and, thereby, adjustable considering light conditions and tracking target's information availability.
Visitor orientation	Only a 2D map was used to provide positional information to the visitor.	2D map is complemented by an extended environment feature to improve visitor's insight about its surroundings, with LOD0 buildings floating near of their respective POIs.

Regarding tests made to the enhanced version of MixAR system, 18 participants carried out MR experiences that took place in an archaeologically relevant site - Vila Velha (Vila real, Portugal) - wherein both immersive and non-immersive MARS were experimented. After the tests, participants gave their feedback by fulfilling a questionnaire that was used to analyse their satisfaction, presence, immersion (SUS-like approach), comfort and sickness (simple occurrence score). On the one hand, some problems related with buildings visualization, their stability and experience's engagement were identified. Outdoors' conditions seem to constitute the main reason for that, followed by models' lack of illumination and re-lightning. On the other hand, easiness to adapt to the experience, desire to see it in museums and a raised curiosity and motivation contributed as positive points for evaluation. In what regards to sickness and comfort, the low number of complaints seems to be satisfactory.

Although Apple (Cupertino, U.S.A) has acquired Metaio SDK resulting in its discontinuation, the proposed multi-tracking approach is still valid for most of the currently available AR SDKs: for example, Vuforia or EasyAR. Thus, future work shall focus on the selection of the most suitable AR SDK (based on their features/specifications) followed by its adaption to work with the approach proposed in this paper. Illumination and re-lightning shall also be addressed to endow augmentation models with a convincing realism. Ideally, a future version of the multi-tracking approach should be able to recognize environmental parameters to adapt the proper tracking technique, at runtime.

ATTACHMENT A

DECLARATION OF CONSENT

Scope: MixAR Project (BI/MIXAR/38803/UTAD/2014) - a mixed reality system for the reconstruction of cultural heritage sites.

Experience realization terms

This experience aims the collection of opinion on comfort, presence, immersiveness and satisfaction, within the scope of the aforementioned project. This experience includes visualization of mixed reality contents.
The participants are volunteers that do not receive any benefits for carrying out the experience. At any time, they may quit from the experience, since they are not bound by any obligation.
All information collected will be anonymized and used for scientific purposes, only.
Experience consists in a set of tasks (procedures). Participants will be instructed during the performance of such tasks, which may vary from test to test.
This experience has been preliminary assessed to ensure that probabilities related to the occurrence of injuries among participants are minimal.
The researcher directly dealing with each participant is available to clarify any additional doubts related with the experience, before its beginning.

Declaration

I declare that I have read and agree with the terms of the experience that I am about to perform, acknowledging my right to quit from it at any moment. Data collected during the experience with a direct or indirect association to me can be used exclusively for scientific purposes, under my consent.

Signature:____

Date: ____ /____ /____

Generic Questionnaire

Age: _____ **Gender:** Male ☐ Female: ☐

Does the subject uses glasses? Yes ☐ No ☐

Occupation: __________________________________

Academic Qualifications

Primary Education ☐ Secondary Education ☐ Higher Education ☐

What is your expertise area?

____

How do you classify your experience with computers?

None ☐ Basic ☐ Average ☐ Good ☐ Advanced ☐

Are you skillful with smartphones?	Yes ☐	No ☐	
If yes, in which operative system(s)?	Android ☐	iOS ☐	Windows Phone ☐
Are you skillful with tables?	Yes ☐	No ☐	
If yes, in which operative system(s)?	Android ☐	iOS ☐	Windows ☐
Have you ever had any contact with augmented reality?	Yes ☐	No ☐	Yes ☐
Have you ever had any contact with virtual reality?	Yes ☐	No ☐	Yes ☐

Experience device: ____

ID:__________

For each question groups, please, mark the answers that better fits the experience that you have just carried out, by selecting one single level between “Completely disagree” to “Completely in agree”, inclusively.

Satisfaction Questionnaire

	Question	Completely disagree	Disagree	Neutral	Agree	Completely agree
1.	I would repeat the experience again	●	●	●	●	●
2.	I liked the contents presented to me	●	●	●	●	●
3.	It was hard to visualize virtual buildings during the experience	●	●	●	●	●
4.	Devices used in the experience were heavy and hard to carry	●	●	●	●	●
5.	Overall, I was pleased with the virtual building models quality	●	●	●	●	●
6.	Virtual contents were seamlessly merged with the real world	●	●	●	●	●
7.	Virtual models were presented robustly (without jumps) and fluidly	●	●	●	●	●
8.	I had the feeling that I was travelling to the past	●	●	●	●	●
9.	I would use this system to visualize virtual reconstructions in archaeological sites	●	●	●	●	●
10.	Overall, I enjoyed the experience that I just performed	●	●	●	●	●

Presence Questionnaire

	Question	Completely disagree	Disagree	Neutral	Agree	Completely agree
1.	I felt involved in the experience	●	●	●	●	●
2.	I was aware of what was going on in the real world (outside the experience)	●	●	●	●	●
3.	I was able to abstract from the devices that I was using in the experience	●	●	●	●	●
4.	I was capable of getting closer to the virtual buildings to observe them	●	●	●	●	●
5.	I was able to visualize the virtual buildings from different viewpoints	●	●	●	●	●
6.	I felt confused and disoriented during the experience	●	●	●	●	●
7.	I felt there was a lag between my actions and the presented virtual content	●	●	●	●	●
8.	I adapted myself to the experience, easily	●	●	●	●	●
9.	I felt that was easy to move around the environment	●	●	●	●	●
10.	I felt that the visual quality prejudiced task execution in the experience	●	●	●	●	●
11.	I was able to focus more in tasks than in devices	●	●	●	●	●
12.	I was so involved that I lost myself in time	●	●	●	●	●

Immersiveness Questionnaire

Question		Completely disagree	Disagree	Neutral	Agree	Completely agree
1.	I was interested in learning what was about to happen along the experience	●	●	●	●	●
2.	I was intrigued with what could happen in each experience task	●	●	●	●	●
3.	Presented virtual contents' quality seemed good to me	●	●	●	●	●
4.	I was able to freely move in the environment	●	●	●	●	●
5.	I felt that virtual buildings belonged to the real world	●	●	●	●	●
6.	While it lasted, the experience was my only concern	●	●	●	●	●
7.	It seems that a short time has passed since the beginning to the end of the experience	●	●	●	●	●
8.	The experience held my attention	●	●	●	●	●
9.	I forgot my daily worries during the experience	●	●	●	●	●
10.	I felt that I was experiencing a new situation, more than just being committed to the realization of some tasks	●	●	●	●	●
11.	I felt motivated along the experience	●	●	●	●	●
12.	I felt that I carried out the experience with success	●	●	●	●	●
13.	I felt disappointed with the experience's ending	●	●	●	●	●

Comfort Questionnaire

From the following possibilities, point out the body zones in which you felt tiredness or exhaustion during or after the experience (none, one or several can be marked):

Generalized fatigue: ☐ Legs: ☐

Shoulders: ☐ Arms: ☐

Back: ☐ Nasal dorsum: ☐

Other: ______________________________

From the following possibilities, point out the types of malaise that affected you during or after the experience (none, one or several can be marked):

Dizziness ☐ Disorientation ☐

Vertigo ☐ Faint feeling ☐

Nausea ☐ Headache ☐

Eye strain	☐	Blurred vision	☐
Vision focus difficulties	☐	Concentration problems	☐

ACKNOWLEDGMENTS

This work is partially supported by the European Fund for Regional Progress — FEDER (Fundo Europeu de Desenvolvimento Regional) through the project 2014/038803 entitled "MixAR — Adaptive Mixed Reality System for Archaeological Sites".

REFERENCES

Adão, T., Magalhães, L., & Peres, E. (2016). *Ontology-based Procedural Modelling of Traversable Buildings Composed by Arbitrary Shapes*. Cham: Springer International Publishing. Retrieved from http://link.springer.com/10.1007/978-3-319-42372-2

ARKit - Apple Developer. (n.d.). Retrieved September 27, 2017, from https://developer.apple.com/arkit/

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355.

Bajura, M., & Neumann, U. (1995). Dynamic registration correction in video-based augmented reality systems. *IEEE Computer Graphics and Applications*, *15*(5), 52–60. https://doi.org/10.1109/38.403828

Bellini, A., Luddi, C., Naldini, S., Ghetti, C., Bellini, E., & Bergamin, G. (2013). "Once Upon A Time": A Proof of Concept Augmented Reality Collaborative Mobile Application to Discover City Heritage (pp. 358–363). Presented at the International Conference on Signal-Image Technology & Internet-Based Systems (SITIS), IEEE. https://doi.org/10.1109/SITIS.2013.65

Billinghurst, M., Clark, A., & Lee, G. (2015). A Survey of Augmented Reality. *Foundations and Trends® in Human–Computer Interaction*, *8*(2–3), 73–272. https://doi.org/10.1561/1100000049

Blanco-Fernández, Y., López-Nores, M., Pazos-Arias, J. J., Gil-Solla, A., Ramos-Cabrer, M., & García-Duque, J. (2014). REENACT: A step forward in immersive learning about Human History by augmented reality, role playing and social networking. *Expert Systems with Applications*, *41*(10), 4811–4828. https://doi.org/10.1016/j.eswa.2014.02.018

Brancati, N., Caggianese, G., Pietro, G. D., Frucci, M., Gallo, L., & Neroni, P. (2015). Usability Evaluation of a Wearable Augmented Reality System for the Enjoyment of the Cultural Heritage (pp. 768–774). IEEE. https://doi.org/10.1109/SITIS.2015.98

Brooke, J. (1996). SUS - A quick and dirty usability scale. *Usability Evaluation in Industry*, *189*(194), 4–7.

Bruno, F., Bruno, S., De Sensi, G., Luchi, M.-L., Mancuso, S., & Muzzupappa, M. (2010). From 3D reconstruction to virtual reality: A complete methodology for digital archaeological exhibition. *Journal of Cultural Heritage*, *11*(1), 42–49. https://doi.org/10.1016/j.culher.2009.02.006

Bustillo, A., Alaguero, M., Miguel, I., Saiz, J. M., & Iglesias, L. S. (2015). A flexible platform for the creation of 3D semi-immersive environments to teach Cultural Heritage. *Digital Applications in Archaeology and Cultural Heritage*, *2*(4), 248–259. https://doi.org/10.1016/j.daach.2015.11.002

Carrozzino, M., & Bergamasco, M. (2010). Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of Cultural Heritage*, *11*(4), 452–458. https://doi.org/10.1016/j.culher.2010.04.001

Cho, Y., & Neumann, U. (1998). Multi-ring color fiducial systems for scalable fiducial tracking augmented reality. In *vrais* (Vol. 98, p. 212). Citeseer. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.45.1741&rep=rep1&type=pdf

Dahne, P., & Karigiannis, J. N. (2002). Archeoguide: system architecture of a mobile outdoor augmented reality system. In *International Symposium on Mixed and Augmented Reality, 2002. ISMAR 2002. Proceedings* (pp. 263–264). https://doi.org/10.1109/ISMAR.2002.1115103

Davison, A. J., Reid, I. D., Molton, N. D., & Stasse, O. (2007). MonoSLAM: Real-Time Single Camera SLAM. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *29*(6), 1052–1067. https://doi.org/10.1109/TPAMI.2007.1049

Dieck, M. C. tom, & Jung, T. (2018). A theoretical model of mobile augmented reality acceptance in urban heritage tourism. *Current Issues in Tourism*, *21*(2), 154–174. https://doi.org/10.1080/13683500.2015.1070801

Duguleana, M., Girbacia, F., Postelnicu, C., Brodi, R., & Carrozzino, M. (2016). Exploring Pisa Monuments Using Mobile Augmented Reality. *World Academy of Science, Engineering and Technology, International Journal of Computer, Electrical, Automation, Control and Information Engineering*, *10*(11), 1719–1722.

EasyAR. (n.d.). Retrieved September 27, 2017, from https://www.easyar.com/

Fiore, A., Mainetti, L., Manco, L., & Marra, P. (2014). Augmented reality for allowing time navigation in cultural tourism experiences: a case study. In *International Conference on Augmented and Virtual Reality* (pp. 296–301). Springer.

Fritz, F., Susperregui, A., & Linaza, M. T. (2005). Enhancing cultural tourism experiences with augmented reality technologies. Presented at the 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST). Retrieved from http://195.130.87.21:8080/dspace/handle/123456789/653

Gaugne, R., Barreau, J.-B., Le Cloirec, G., & Gouranton, V. (2013). Experiencing the past in virtual reality: A virtual reality event for the french national days of archaeology. In *Cognitive Infocommunications (CogInfoCom), 2013 IEEE 4th International Conference on* (pp. 75–80). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6719200

GeoDataSource. (2017, May 31). Calculate Distance by Latitude and Longitude using PHP. Retrieved May 31, 2017, from http://www.geodatasource.com/developers/php

Han, J.-G., Park, K.-W., Ban, K.-J., & Kim, E.-K. (2013). Cultural Heritage Sites Visualization System based on Outdoor Augmented Reality. *AASRI Procedia*, *4*, 64–71. https://doi.org/10.1016/j.aasri.2013.10.011

Home. (n.d.). Retrieved September 27, 2017, from https://www.kudan.eu/

Ikeuchi, K. (2013). e-Heritage, Cyber Archaeology, and Cloud Museum (pp. 1–7). Presented at the International Conference on Culture and Computing (Culture Computing), IEEE. https://doi.org/10.1109/CultureComputing.2013.77

Jennett, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., & Walton, A. (2008). Measuring and defining the experience of immersion in games. *International Journal of Human-Computer Studies*, *66*(9), 641–661. https://doi.org/10.1016/j.ijhcs.2008.04.004

Jiménez Fernández-Palacios, B., Morabito, D., & Remondino, F. (2016). Access to complex reality-based 3D models using virtual reality solutions. *Journal of Cultural Heritage*. https://doi.org/10.1016/j.culher.2016.09.003

Jung, T. H., Lee, H., Chung, N., & Dieck, M. C. tom. (2018). Cross-cultural differences in adopting mobile augmented reality at cultural heritage tourism sites. *International Journal of Contemporary Hospitality Management*, *30*(3), 1621–1645. https://doi.org/10.1108/IJCHM-02-2017-0084

Kato, H., & Billinghurst, M. (1999). Marker tracking and HMD calibration for a video-based augmented reality conferencing system. In *2nd IEEE and ACM International Workshop on Augmented Reality, 1999. (IWAR ’99) Proceedings* (pp. 85–94). https://doi.org/10.1109/IWAR.1999.803809

Kaufmann, H., & Dünser, A. (2007). Summary of Usability Evaluations of an Educational Augmented Reality Application. In R. Shumaker (Ed.), *Virtual Reality* (pp. 660–669). Springer Berlin Heidelberg. Retrieved from http://link.springer.com/chapter/10.1007/978-3-540-73335-5_71

Kiourt, C., Koutsoudis, A., & Pavlidis, G. (2016). DynaMus: A fully dynamic 3D virtual museum framework. *Journal of Cultural Heritage*, *22*, 984–991. https://doi.org/10.1016/j.culher.2016.06.007

Koller, D., Daniilidis, K., & Nagel, H. H. (1993). Model-based object tracking in monocular image sequences of road traffic scenes. *International Journal of Computer 11263on*, *10*(3), 257–281. https://doi.org/10.1007/BF01539538

Lepetit, V., Fua, P., & others. (2005). Monocular model-based 3d tracking of rigid objects: A survey. *Foundations and Trends® in Computer Graphics and Vision*, *1*(1), 1–89.

Lim, V., Frangakis, N., Tanco, L. M., & Picinali, L. (2018). PLUGGY: A Pluggable Social Platform for Cultural Heritage Awareness and Participation. In *Advances in Digital Cultural Heritage* (pp. 117–129). Springer, Cham. https://doi.org/10.1007/978-3-319-75789-6_9

Lima, J. P. S. do M., Simoes, F. P. M., Figueiredo, L. S., & Kelner, J. (2010). Model Based Markerless 3D Tracking applied to Augmented Reality. *SBC Journal on Interactive Systems*, *1*(1), 2–15.

Lourakis, M. I. A., & Argyros, A. A. (2005). Efficient, Causal Camera Tracking in Unprepared Environments. *Computer Vision and Image Understanding Journal*, *99*, 259–290.

Magalhaes, L. G., Sousa, J. J., Bento, R., Adao, T., Pereira, F., Filipe, V., & Peres, E. (2014). Proposal of an Information System for an Adaptive Mixed Reality System for Archaeological Sites. *Procedia Technology*, *16*, 499–507. https://doi.org/10.1016/j.protcy.2014.10.117

Marchand, É., Bouthemy, P., & Chaumette, F. (2001). A 2D–3D model-based approach to real-time visual tracking. *Image and Vision Computing*, *19*(13), 941–955. https://doi.org/10.1016/S0262-8856(01)00054-3

Marques, L. F., Tenedório, J. A., Burns, M., Romão, T., Birra, F., Marques, J., … others. (2017). Cultural Heritage 3D Modelling and visualisation within an Augmented Reality Environment, based on Geographic Information Technologies and mobile platforms.

Metaio (Munich, Bayern). (n.d.). Retrieved May 28, 2015, from http://www.metaio.com

Microsoft. (n.d.). Microsoft HoloLens. Retrieved September 27, 2017, from https://www.microsoft.com/en-us/hololens

Miles, H. C., Wilson, A. T., Labrosse, F., Tiddeman, B., Griffiths, S., Edwards, B., … others. (2016). Alternative representations of 3D-reconstructed heritage data. *Journal on Computing and Cultural Heritage (JOCCH)*, *9*(1), 4.

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1994). Augmented Reality: A class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies*, *2351*, 282–292.

Mortara, M., Catalano, C. E., Bellotti, F., Fiucci, G., Houry-Panchetti, M., & Petridis, P. (2014). Learning cultural heritage by serious games. *Journal of Cultural Heritage*, *15*(3), 318–325. https://doi.org/10.1016/j.culher.2013.04.004

Narciso, D., Pádua, L., Adão, T., Peres, E., & Magalhães, L. (2015). MixAR Mobile Prototype: Visualizing Virtually Reconstructed Ancient Structures In Situ. *Procedia Computer Science*, *64*, 852–861. https://doi.org/10.1016/j.procs.2015.08.638

Olsson, T., & Salo, M. (2011). Online user survey on current mobile augmented reality applications. In *2011 10th IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 75–84). https://doi.org/10.1109/ISMAR.2011.6092372

Olsson, Thomas, Kärkkäinen, T., Lagerstam, E., & Ventä-Olkkonen, L. (2012). User Evaluation of Mobile Augmented Reality Scenarios. *J. Ambient Intell. Smart Environ.*, *4*(1), 29–47.

Pádua, L., Adão, T., Narciso, D., Cunha, A., Magalhães, L., & Peres, E. (2015). Towards Modern Cost-effective and Lightweight Augmented Reality Setups: *International Journal of Web Portals*, *7*(2), 33–59. https://doi.org/10.4018/IJWP.2015040103

Pádua, L., Narciso, D., Adão, T., Cunha, A., Peres, E., & Magalhães, L. (2015). Cost-effective and Lightweight Mobile Units for MixAR: A Comparative Trial among Different Setups. *Procedia Computer Science*, *64*, 870–878. https://doi.org/10.1016/j.procs.2015.08.597

Pedersen, I., Gale, N., Mirza-Babaei, P., & Reid, S. (2017). More than Meets the Eye: The Benefits of Augmented Reality and Holographic Displays for Digital Cultural Heritage. *Journal on Computing and Cultural Heritage*, *10*(2), 1–15. https://doi.org/10.1145/3051480

Porzi, L., Ricci, E., Ciarfuglia, T. A., & Zanin, M. (2012). Visual-inertial tracking on android for augmented reality applications. In *Environmental Energy and Structural Monitoring Systems (EESMS), 2012 IEEE Workshop on* (pp. 35–41). IEEE. Retrieved from http://ieeexplore.ieee.org/abstract/document/6348402/

Pressigout, M., & Marchand, E. (2006). Hybrid tracking algorithms for planar and non-planar structures subject to illumination changes. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 52–55). https://doi.org/10.1109/ISMAR.2006.297794

Robles-Ortega, M. D., Feito, F. R., Jiménez, J. J., & Segura, R. J. (2012). Web technologies applied to virtual heritage: An example of an Iberian Art Museum. *Journal of Cultural Heritage*, *13*(3), 326–331. https://doi.org/10.1016/j.culher.2011.10.001

Rua, H., & Alvito, P. (2011). Living the past: 3D models, virtual reality and game engines as tools for supporting archaeology and the reconstruction of cultural heritage – the case-study of the Roman villa of Casal de Freiria. *Journal of Archaeological Science*, *38*(12), 3296–3308. https://doi.org/10.1016/j.jas.2011.07.015

Rubino, I., Barberis, C., Xhembulla, J., & Malnati, G. (2015). Integrating a Location-Based Mobile Game in the Museum Visit: Evaluating Visitors' Behaviour and Learning. *Journal on Computing and Cultural Heritage*, *8*(3), 1–18. https://doi.org/10.1145/2724723

Stricker, D., Dähne, P., Seibert, F., & al, et. (2001). Design and development issues for ARCHEOGUIDE: An Augmented Reality based cultural heritage on-site guide. In *International Conference on Augmented, Virtual Environments and Three-Dimensional Imaging. Proceedings* (pp. 1–5).

Tango. (n.d.). Retrieved September 27, 2017, from https://get.google.com/tango/

Teichrieb, V., Lima, J. P. S. do M., Apolinário, E. L., Farias, T. S. M. C. de, Bueno, M. A. S., Kelner, J., & Santos, I. H. F. (2007). A Survey of Online Monocular Markerless Augmented Reality. *International Journal of Modeling and Simulation for the Petroleum Industry*, *1*(1). Retrieved from http://m2ssoftware.org/ojs/index.php/ijmspi/article/view/88

Vacchetti, L., Lepetit, V., & Fua, P. (2004). Combining Edge and Texture Information for Real-Time Accurate 3D Camera Tracking. In *Proceedings of the 3rd IEEE/ACM International Symposium on Mixed and Augmented Reality* (pp. 48–57). Washington, DC, USA: IEEE Computer Society. https://doi.org/10.1109/ISMAR.2004.24

van Krevelen, D., & Poelman, R. (2010). A Survey of Augmented Reality Technologies, Applications and Limitations. *The International Journal of Virtual Reality*, *9*(2), 1–20.

Vlahakis, V., Ioannidis, N., Karigiannis, J., Tsotros, M., Gounaris, M., Stricker, D., … Almeida, L. (2002). Archeoguide: an augmented reality guide for archaeological sites. *IEEE Computer Graphics and Applications*, *22*(5), 52–60. https://doi.org/10.1109/MCG.2002.1028726

Vuforia Developer Portal |. (n.d.). Retrieved September 27, 2017, from https://developer.vuforia.com/

Wikitude - Get Started With The World's Leading Cross-Platform AR SDK. (n.d.). Retrieved September 27, 2017, from https://www.wikitude.com/

Witmer, B. G., & Singer, M. J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225–240. https://doi.org/10.1162/105474698565686

Zhou, X., Zhou, X., Kobashi, K., & Sugihara, K. (2016). Development of history learning support system: 3D virtual reconstruction and visualization of ancient Japanese architectures. In *Computer Science & Education (ICCSE), 2016 11th International Conference on* (pp. 317–320). IEEE.