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Combining paper maps and smartphones in the exploration of cultural heritage

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To my closest friends and family.

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Abstract

Latest advances in technology allowed us to have, nowadays, powerful computing devices in our pockets. These advances have also allowed the rapid growth of Augmented Reality, which continues to expand into new areas where the integration of virtual and real worlds brings new and beneficial experiences.

It is on these Augmented Reality capable devices that there may be a key that will open a door to a new experience in exploring cultural and historical sites, currently very dependent on paper and static information maps or mobile interactive applications that, although capable of providing real-time information, may not give users a contextualized view of the different cultural elements in their surrounding environment.

The goal of this dissertation is to explore new ways to interact and view content associated with a cultural and historical site through a smartphone-focused application with Augmented Reality and location-aware features. Combining a paper map with a smartphone, the user can see virtual representations of sites, manipulate them in 3D, overlap historical cartography on the map or view relevant multimedia information, among others. In an effort to raise awareness of less known sites or whose location isn't immediately apparent, the application alerts the user about sites near his position.

Then, the application underwent various tests by potential users, in order to evaluate its concept and usability.

In the end, it is expected to develop a new user interactive experience, as an attempt to increase interest and awareness of cultural and historic sites and their roles, and formulate recommendations on the development of heritage-oriented applications.

Keywords: Augmented Reality, mobile devices, human-computer interaction, paper maps, cultural and historic heritage, location-aware services

Resumo

Os rápidos avanços na tecnologia permitiram que, hoje em dia, tenhamos poderosos dispositivos de computação nos nossos bolsos. Estes avanços permitiram também o rápido crescimento da Realidade Aumentada, que continua a expandir-se para novas áreas onde é possível integrar o mundo virtual com o mundo real para trazer novas e benéficas experiências.

É nestes dispositivos capazes de Realidade Aumentada que pode estar uma chave que permitirá abrir uma porta de uma nova experiência de exploração do património cultural e histórico, actualmente muito dependente de mapas e informação estática em papel ou aplicações interactivas que, embora sejam capazes de fornecer informação em tempo real, podem não conseguir dar ao utilizador uma vista contextualizada dos vários elementos culturais no seu redor.

O objectivo desta dissertação será explorar novas maneiras de interacção com o património cultural e histórico, visualizando conteúdo associado a um espaço através de uma aplicação com funcionalidades de Realidade Aumentada e de localização vocacionada para smartphones. Combinando um mapa de papel com um smartphone, o utilizador poderá ver representações virtuais dos espaços, manipulá-las em 3D, sobrepor cartografia histórica sobre o mapa, ou consultar um conjunto de elementos multimédia relevantes, entre outros. Num esforço de divulgação de locais menos conhecidos ou cuja localização não seja imediatamente aparente, a aplicação alerta o utilizador da presença desses locais nas suas imediações.

A aplicação foi depois submetida a vários testes com potenciais utilizadores para avaliar o conceito e a sua usabilidade.

No final, espera-se desenvolver uma nova experiência interactiva aos utilizadores que aumente o interesse pelo património e os seus papeis, bem como formular recomendações sobre o desenvolvimento de aplicações vocacionadas para o património.

Palavras-chave: Realidade Aumentada, dispositivos móveis, interacção-pessoa máquina, mapas de papel, património cultural e histórico, serviços de localização

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Chapter 1

Introduction

This first chapter introduces the context where this dissertation fits and the motivation behind it. Then it formalizes the problem identified and presents a proposed approach to solve it. Finally, this chapter outlines the expected contribution of this dissertation and the structure of the rest of document.

1.1 Motivation and Context

Over the course of history, mankind had the need to adapt and develop various infrastructures to improve life, whether for subsistence or means of leisure. Such achievements, which had an important contribution to modern life, are represented by sites that resisted the flow of time and are considered as part of our cultural and historic heritage.

Often overlooked, these sites can go unnoticed by potential visitors and curious people. Exploring new ways of interaction and raising public awareness of these sites is a challenge in a modern society, where people tend to be with their heads down focused on smartphones, oblivious of their surroundings.

Advancements in technology in recent years made possible to have almost the entire world inside our pocket, thanks to smartphones. Small yet powerful, they offer an extensive amount of resources such as location sensors, camera, internet access and graphics processing. This potential can be explored for its ubiquity and interactive capabilities, allowing the development of mobile applications that open a new door for the communication between the user and the heritage of cultural and historic sites.

This dissertation was developed in collaboration with Luís Marques working at *Inspecção-Geral da Agricultura, do Mar, do Ambiente e do Ordenamento do Território*[1] and a PhD student at *Escola Tècnica Superior d'Arquitectura de Barcelona - Universitat Politècnica de*

[1] http://www.igamaot.gov.pt/

Catalunya[2] co-advised by Professor José António Tenedório from *Faculdade de Ciências Sociais e Humanas - Universidade Nova de Lisboa*[3]. Luís provided 3D models and various multimedia content of the *Águas Livres* aqueduct system which will be detailed in chapter 3.

1.2 Problem Description

Public awareness of cultural and historical sites is correlated with the way they are presented to potential visitors. Often that kind of sites can go unnoticed by passersby or less informed tourists, due to poor or inexistent information of their existence.

Worn out panels like the one seen on figure 1.1 and no information available on the user's native language are some of the ways to sever this communication link between visitors and sites, leaving interested people oblivious of the heritage and major roles those sites once had on their historical timeline.

Figure 1.1: A worn-out panel that held content about the castle of *Almourol*, *Tancos*, *Portugal*

Even when those problems aren't visibly present, information displayed often consists of static elements, making the human interaction reduced to simply watching, reading or moving to the next place. Devices specialized on interactivity require some investment and maintenance costs that are usually unsustainable by the organization that takes care of the place, effectively putting out of commission interactive content such as simulation of water movement on an aqueduct or picture overlapping.

A paper tour map and a smartphone are two items that are usually part of a tourist's inventory. A tour map is easy to find and carry, has basic (and static) information [31] about major cultural sites and their location and sometimes small 2D representations.

[2] http://www.etsab.upc.edu/
[3] http://www.fcsh.unl.pt/

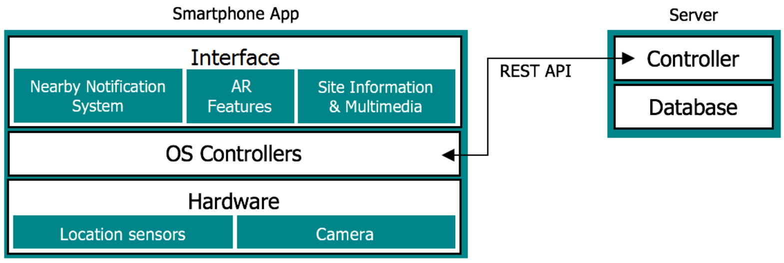


Figure 1.2: System architecture

They provide a friendly, familiar and easy way to plan a visit or navigate in a city and a wide overview of the area they cover, something hard to achieve in a small screen of a mobile device, specially for an overall analysis of long routes. According to Brown and Chalmers [4], a paper map is an important tool for tourists, along with a guidebook.

However, further detailed information often requires getting additional pamphlets or using the smartphone (provided that an internet connection is available) for a web search that may not be as quick as expected because of a possible need to filter unwanted results.

How to address these problems and at the same time provide the user with an interactive experience?

1.3 Proposed Approach

The proposed approach takes advantage of the benefits of paper maps and overcomes their limitations. With the use of AR we can transform a paper map into a dynamic map capable of delivering contextual information to its users in real-time. Because this information is dynamic, it's easy to update without the need to reprint and replace its base paper map and it can be theoretically infinite, giving the users the option to select which piece of information they want to view at a given moment, as not to clutter the screen [11].

This approach has three main components for its architecture (see Figure 1.2): An Augmented Reality component for displaying virtual objects on the paper map, a multimedia component where each cultural site has associated content (updatable through a web server) and a location-aware component that will help the user discovering cultural sites, that may not be easily spotted on a normal sightseeing tour. With these components, the system hopes to answer the questions "What's that?" and "What's here?", two important questions that mobile tour systems need to support according to Davies et. al [7].

It is centered on a mobile smartphone application (app) targeted to Android devices, with features that aim to enhance the user experience while touring and exploring historical and cultural heritage sites. More information will be detailed in chapter 3.

This system allows a broader awareness of cultural and historical heritage, helping users preparing their visits beforehand and notifying them about interesting and lesser known sites, that may be near them while traveling the city and informing about historic content and details of the site's role.

As a working example, the application will be using the *Águas Livres* aqueduct system (Figure 1.3) in Lisbon, Portugal as a basis. The *Águas Livres* aqueduct system was built

(a) The iconic arches of the *Alcântara* valley

(b) *Loreto* gallery, one of the few visitable underground tunnels (galleries)

(c) The aqueduct's final pathway diagram as it enters Lisbon

Figure 1.3: A portion of the *Águas Livres* aqueduct system

in the 18th century as an effort to solve the problem of lack of drinking water in the city. A quick web search usually shows us the most iconic part of the aqueduct pathway, which are the arches over the *Alcântara* valley, but in fact that's only a little part of the whole system, composed of many fountains, reservoirs and a vast underground network of tunnels scattered over Lisbon, part of them open to visits. The variety of sites associated with the whole system, their not so directly apparent connection and different levels of public awareness were the key factors in choosing the *Águas Livres* aqueduct.

1.4 Contributions

The mobile application and the research done on new ways to explore the cultural and historic heritage sites are the main contributions of this dissertation. Research has been done on the interaction with Augmented Reality systems that combine the use of paper maps and smartphone and their impact in public awareness of the related sites.

The developed work hopes to bring more public awareness to cultural and historic sites, (in this case the *Águas Livres* aqueduct) with new ways of interaction and to give the user an intuitive experience in exploring new types of views, historic content and details of the site's role.

User feedback will be important not only for studying the impact of these types of augmented experiences on people's cultural awareness and navigation when exploring cultural elements in a city, but also for input for current work and recommendations for future development.

Finally, this dissertation's work is reflected on two papers, one published and presented at the EPCGI'2016 in Covilhã on 25th November 2016 [24], and the other accepted for future publication in the ACE magazine [16].

1.5 Document Organization

In addition to this chapter, the rest of the document is organized as follows:

- **Chapter** 2 addresses the related work on the Augmented Reality concept in detail and introduces some case studies directly or indirectly related to the context of this dissertation. It also mentions tools for developing AR-enabled software and wraps up with a brief discussion.

- **Chapter** 3 details the implementation of the proposed approach, describing the experimental work done, the system's components and how major drawbacks were overcame.

- **Chapter** 4 is dedicated to the testing of the proposed approach done by potential users and to the analysis of their evaluation and feedback.

- **Chapter** 5 wraps up the dissertation with an overall discussion and conclusions made from the users' evaluation. Based on the investigation done, this chapter proposes guidelines for this type of applications and denotes future work to the proposed approach.

Chapter 2

Related Work

This chapter starts by describing the Augmented Reality (AR) concept, a major component of this dissertation's approach, detailing methods and techniques of displaying and aligning it with the real world. Next, it introduces some notable case studies done in the AR department, some of which close to the context of this dissertation. Then, this chapter examines some examples of tools available for Augmented Reality, and finally wraps up with a brief discussion.

2.1 Augmented Reality

According to Milgram and Kishino [18], Augmented Reality can be located between the real world and the Virtual Reality environments in the Virtuality Continuum (figure 2.1). It is part of the Mixed Reality environment concept where real and virtual objects are present together in the same view. It is a technology that allows the user to observe the real world with imposed virtual objects in a way that they seem to co-exist in the same space as real world objects. Azuma et al. [1] defines AR systems to share these properties:

- Brings real and virtual objects together in a real environment.
- Is real-time interactive.
- Aligns virtual and real objects in three dimensions.

2.1.1 Displaying Augmented Reality

One of the first steps in building an AR system is to decide the technology to use, based on the system's needs. Azuma [2] establishes two choices of technology: Optical and Video, each one with their benefits and drawbacks. Head-Mounted Displays (HMD) were one

Figure 2.1: Milgram's [18] Virtuality Continuum diagram

of the first devices that made Augmented Reality possible. They were used, for example, in military aircraft providing basic navigation and flight information by a see-through lenses, that allowed the pilot to see the real world with said information superimposed.

2.1.1.1 Optical Technology

Optical technology such as optical see-through HMD's works by placing optical combiners in front of the user's eyes. They are partially transmissive and reflective, so that the user can view the real world through them at the same time he sees virtual images created by the scene generator as seen on the diagram in figure 2.2. Depending on the used hardware, this direct view of the real world may have some drawbacks: only a fraction of the real world light reaches the user's eyes and while the real world is seen without any delay, there may exist some lag on virtual images. However in case of system failure, the user can still view the real world albeit with that portion of missing light (similar to when wearing a pair of sunglasses). Google Glass[1] and the upcoming Microsoft Hololens[2] are examples of optical AR displays.

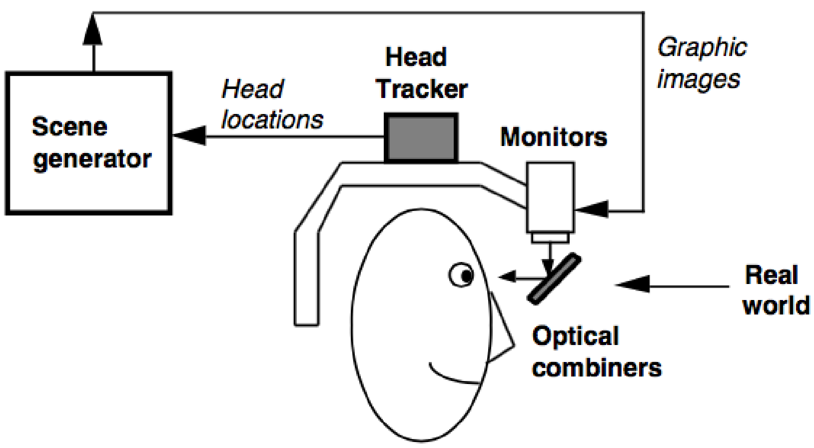


Figure 2.2: Azuma's [2] conceptual diagram of an optical HMD

[1] http://www.google.com/glass
[2] https://www.microsoft.com/microsoft-hololens/

2.1.1.2 Video Technology

Video technology relies on video cameras to display the real world to the user. This technology is used by another type of HMD's and monitor-based systems.

Video see-through HMD's combines a closed-view HMD with head mounted video cameras that capture and provide the user's view of the real world combined with virtual images created by the scene generator. A diagram by Azuma [2] can be seen in figure 2.3. In case of failure the user can no longer view the real world through the video HMD's, unlike their optical counterparts. The Oculus Rift[3] is an example of video head-mounted display.

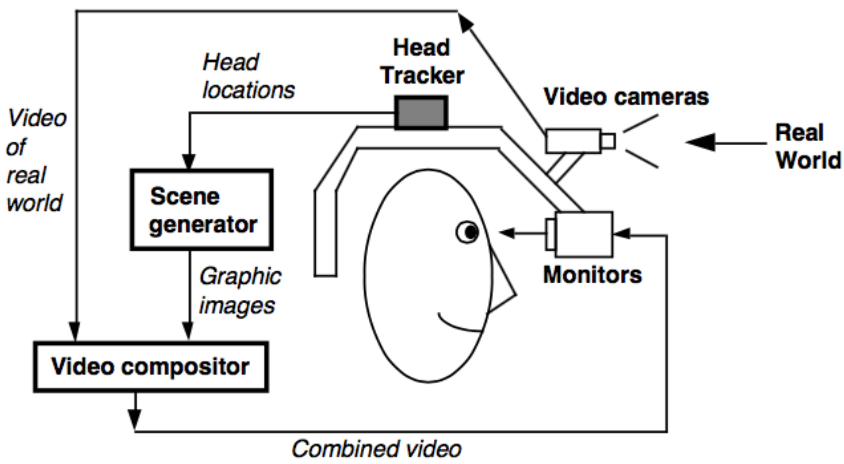


Figure 2.3: Azuma's [2] conceptual diagram of a video HMD

Monitor-based systems include one or two cameras to capture the real environment and display it combined with the virtual generated images on a display monitor in front of the user, like shown on figure 2.4. Any device with a camera, screen and the appropriate software can be considered an AR system of this type. Rekimoto called this *"the magnifying glass metaphor approach"* when he proposed a system called the **NaviCam** that consisted of a small LCD-TV, CCD camera and a gyro sensor [27]. Advancements in technology made possible to incorporate this concept in modern day devices like smartphones, portable computers and videogame systems. In fact, the high portability of these systems led to the growth of AR games like the one seen in figure 2.5. Notably handheld displays are *"a good alternative to HMD [...] systems for AR applications, particularly because they are minimally intrusive, socially acceptable, readily available and highly mobile"* according to Zhou et al. [35].

[3] https://www.oculus.com/en-us/rift/

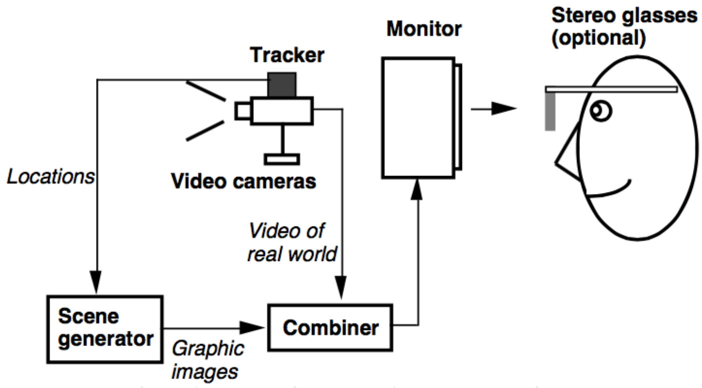


Figure 2.4: Azuma's [2] conceptual diagram of a monitor based AR system

2.1.2 Tracking Techniques

Tracking is the most popular researched topic according to Zhou et al. [35]. There are two main techniques used for tracking - sensor and vision based - that can be used independently or in conjunction (hybrid technique).

2.1.2.1 Sensor Based Tracking

This technique relies on sensors such as GPS, gyroscopes, accelerometers and magnetometers in order to find the location and orientation of real world objects. Rolland et al. [28] identifies six main principles of sensor based tracking:

- **Time of Flight** relying on measuring distances between sensors attached to targets via the time of propagation of pulsed signals.
- **Spatial Scan** using beacons and sensors, where the beacon is in a fixed position and the sensors on the targets (inside-out) or the other way around (outside-in).
- **Inertial Sensing** attempting to conserve a given axis of rotation (gyroscope) or a position (accelerometer).
- **Mechanical Linkages** using mechanical parts that can be used to compute the orientation via incremental encodings. Wires rolled on coils in a spring system are tensed to measure distance.
- **Phase-Difference** measures the difference of a target's incoming signal with a comparison signal located on the reference, sharing the same frequency. Sutherland's system [32] used this type of tracking in the 1960s.
- **Direct-Field Sensing** using a known field, such as Earth's magnetic and gravitational field, to get orientation and position.

2.1.2.2 Vision Based Tracking

This technique uses image processing methods to calculate the camera's pose in relation to real world objects.

Marker-based methods determines the camera pose in real time from artificial markers recognized by detecting marker properties known to the processing algorithm (such as patterns or corners). With this information it is possible to calculate and position a virtual object within the real world scene captured by the camera, according to the marker's position and orientation. Think of a marker as a portal between real and virtual realms - without it, the virtual object cannot be placed in the real world. Some videogames use a marker-based methods such as *Kid Icarus: Uprising* for the *Nintendo 3DS* in its AR game mode, as seen in figure 2.5.

Figure 2.5: *Kid Icarus Uprising* uses a marker-based technique for its AR game mode

Feature-based methods rely on points, edges, textures and other naturally occurring features to determine the camera's pose. With the pose known, additional captured features can be used to extend tracking and update position. According to Zhou et al. [35], *"the most recent trend in computer vision tracking techniques [...] is model-based tracking methods"*. A model of features of tracked objects is used to track their location on the real world. As edges are efficient to find and illumination resistant, they are the most frequently used features.

2.2 Case Studies

Many case studies were developed in order to explore the full potentials of mixing virtual and real world realms.

One notable example in historic heritage is **Archeoguide**. As defined by Vlahakis et al. [34], it stands for "Augmented Reality-Based Cultural Heritage On-Site Guide". It was designed to be an electronic guide to historic sites. The system consisted of a client-server architecture with 3 different type of mobile clients: A laptop with a HMD for Augmented Reality displaying 3D models of sites like they used to be and offering a personalized tour based on the user's profile, a tablet that used DGPS for navigation and a palmtop (a precursor of smartphones) that presented information at certain points and augmented multimedia, like an animation of virtual athletes competing on a site that once was a stadium.

Olympia was the place chosen for testing, where three access points were installed in order to provide a network connection and a DGPS beacon to correct GPS position. The test received good reviews with the major issues being some users feeling uncomfortable in wearing the HMD and the small screen of the palmtop. The application of this dissertation aims to bring together many features of the 3 separate clients like the animations present on the palmtop and the AR component of the laptop.

One of the earliest case studies is **Touring Machine: A prototype campus information system**. This prototype aimed to use AR in order to make an interactive information system about buildings of an university campus based on the location and users' field of view. As the researchers wanted to use off-the-shelf hardware for this experimental prototype, the system weighted about 40 pounds and consisted of a backpack computer, a handheld computer, HMD, and orientation and GPS position trackers [8].

With advancements on technology., all this hardware can fit on a small device such as a smartphone. That led to further explorations of this concept with case studies like **SwissPeaks**, which used a smartphone's camera and GPS sensor to help identifying mountain peaks of Switzerland [12], and in commercial apps. In Portugal, *Grande Rota do Vale do Côa*[4] and *Rota do Românico*[5] are examples of commercial cultural and historic heritage related applications that explore this concept. These applications rely on location and camera to display 2D content over the captured image, rather than the paper map with 3D models approach that this dissertation's application aims to achieve.

MapLens is another case study close to the context of this dissertation. This case study compared the use of two different solutions in group collaborative tasks. One solution (called DigiMap) relied only on a smartphone with built in map software, while the other said device augmented a paper-city map in a context Morrison et al. [20] call "magic lens", hence the name MapLens. In both solutions the smartphone would display information such as text or images about certain points that were visible at the moment (either by

[4] http://granderotadocoa.pt/
[5] http://www.rotadoromanico.com/

displaying the built-in map with DigiMap or the part of the map captured by the camera with MapLens).

A test in form of a location and team-based treasure hunt game was run in Helsinki in March 2008. The results showed that although the users of MapLens had some trouble with navigation, as the map needed to be stabilized in order to be detected by the smartphone, these group members worked together and shared the map unlike DigiMap groups where one user used the device and the others observed their surroundings.

This concept of magic lens dates back to early 90's when Fitzmaurice presented a system named **Chameleon** [9], which investigated how palmtop devices can bridge physical objects with computer generated information, aware of their location. Schöning et al. presented a different approach called **Map Torchlight**, which placed virtual elements directly on a physical map through a projector unit [30], rather than viewing them through a screen.

In a similar way to MapLens, **APM: Augment Paper Map** explores the potential that paper maps have when combined with devices with GPS and connectivity capabilities, augmenting said maps with additional content and features via a mobile device. Paelke and Sester focused their work [23] on small water craft navigation. A device is used in conjunction with a paper navigation chart to provide current position, location updates and interactivity such as defining a route and finding out about last minute warnings and changes impossible to visualize on a static piece of paper.

The prototype uses a webcam pointed to a map where a PDA with an ARToolkit marker attached could be used. Based on the marker's distance and rotation from the webcam, ARToolkit through image processing [13], could calculate the PDA's position and orientation with the appropriate information for its location being displayed on the screen. This case study is one of the closest to the context of this dissertation, as while it focused on the use of paper maps in sailing, it can be expanded to other areas, namely the exploration of cultural heritage.

ARTourMap [22] is another interesting example close to the context of this dissertation, as it uses the MapLens concept to display 3D buildings on a paper map, though apparently with no great level of detail and not easily manipulable, as few details are currently available.

2.3 Tools

Nowadays, there is a wide array of tools available for Augmented Reality. From specialized software development kits to libraries with AR extensions, the tools available depend on the platform and the developer's needs. The following subsections describe some examples.

2.3.1 Vuforia

Vuforia[6] (now owned and developed by PTC) is a software development kit originally developed by Qualcomm that makes possible the creation of Augmented Reality applications for mobile devices. Currently, it provides an API both for native Android (Java) and iOS (Objective C) systems and also an Unity game engine extension, making possible the development of an application that can be easily ported to both systems.

It's capable of tracking up to five 2D images simultaneously (called Image Targets)[25] as well as cuboid and cylinder 3D objects. Upon detecting the pre-configured image, Vuforia is able to display virtual objects like 3D models and positioning them according to position and orientation of the detected image target in real time, giving the perception that the virtual objects are part of the environment captured by the device's camera.

2.3.2 OpenCV

OpenCV[7] is an open source computer vision software library. It has hundreds of algorithms including computer vision and machine learning ones that can identify faces, objects, tracking movements, image processing, producing 3D models, among others.

On the AR field, besides the tracking and identification algorithms, OpenCV is capable of recognizing scenery and establish markers on it. There are a number of AR-focused programs and libraries that rely on OpenCV such as OpenAR[8] and ArUco[9].

Being an open-source software, OpenCV is available for many platforms like Windows, Android and MacOS and has interfaces written in C++, C, Python, Java and MATLAB.

2.3.3 Unity

Unity[10] is a specialized game development engine. It supports various devices such as PCs, videogame consoles and handheld devices like smartphones and tablets, providing a multi-platform solution for the developers that want to create 2D and 3D experiences. Coding is made on C#, and it supports extensions to further enhance the platform's capabilities.

AR on Unity is achieved using specialized extensions, such as the previously mentioned Vuforia and UART[11]. Although the main focus of Unity is game development, it is possible to develop applications that although interactive, cannot fall into the category of "pure game", making Unity an interesting platform for applications that aim to support multiple operating systems.

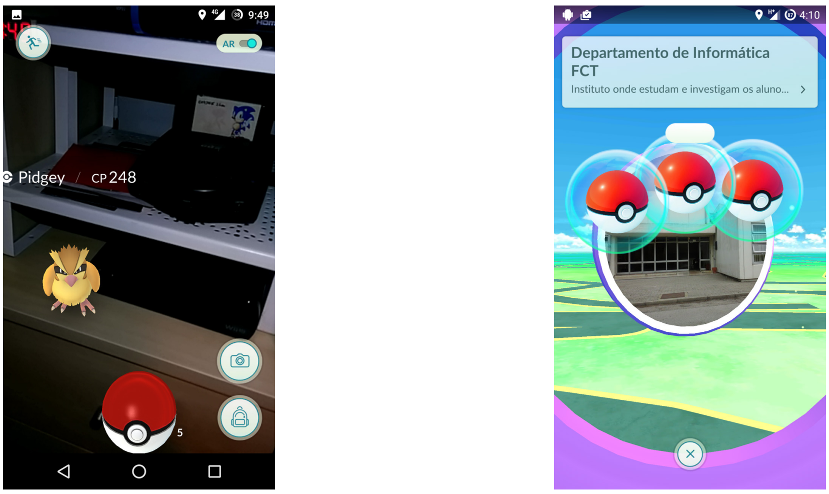
[6] http://vuforia.com
[7] http://opencv.org/
[8] https://github.com/bharathp666/openAR
[9] http://www.uco.es/investiga/grupos/ava/node/26
[10] http://opencv.org/
[11] https://research.cc.gatech.edu/uart/

2.4 Discussion

In this chapter, we analyzed the various technologies related to Augmented Reality, one major focus of this dissertation's work. Although in the early days this way of joining virtual and real objects was very limited to what hardware could offer, achievements over recent years in microprocessing and mobile technology opened a new door for AR to evolve and walk towards a mature state. What in the past was limited to a single user carrying a heavy backpack and a headset that wouldn't be out of place in a futuristic movie, can now be enjoyed be many at the same time, sharing one device that fits well in the palm of the hand.

Tracking techniques also evolved and are more efficient thanks to evolution of hardware and image processing and recognition algorithms, with some techniques dismissing the use of markers and relying on naturally occurring features. All these advancements in recent years allowed the rapid appearance of multiple AR-based experiences, mainly games.

During the writing of this document, a game that takes advantage of historic sites for some of its gameplay mechanics was released to a worldwide success. **Pokémon GO**, released in July 2016 by Niantic Labs, is a game which uses a real world map and the user's smartphone location to place virtual "pocket monsters" in various locations of the real world. The game's objective is for the user (called the trainer) to catch all the different types of Pokémon. If the user is in reach of a Pokémon's location, they will appear on the map and upon interaction, it will be given the chance to catch the monster. The catching process has an AR component that uses the phone's camera to place the Pokémon in the real world as shown in figure 2.6a.



(a) Pokémon catching AR screen

(b) Pokéstop dropping items

Figure 2.6: Some of Pokémon GO's gameplay mechanics

Once caught, the user can, among other things, use the Pokémon for battles with other trainers in special real world locations called "Gyms", that are usually located in a site with relevant historic / cultural role. Players must go to those locations in order to battle and conquer Gyms from rival teams. Besides being Gyms, cultural and historic sites can play another role in the game, as form of a "Pokéstop", where the trainer can walk to and the site will give them items to progress in the game [21]. Released to critical success, Pokémon GO has the potential of raising public awareness of cultural and historic sites, as it encourages users to move within the site's location in order to obtain items or battle and, in some cases, it gives a little background information of the site (figure 2.6b). Whether this potential will have a great impact or not remains to be studied. Although the game has an AR component, it is more considered a "location-based entertainment" (as discussed by Perlin [10]), as the AR experience is limited to place the Pokemon in the camera's view when trying to catch it.

Moreover, a research survey made in Switzerland showed, according to Costanza et al. [6], *"a trend towards more application-specific projects"*. Nowadays, there is a wide variety of tools that help the developer building an AR-based prototype in a short period of time and then tune it and turn it into a fully functional application. Exploring the many possibilities that AR-based mobile applications have to offer in benefit of exploring the vast cultural and historical heritage in a existence is one of the challenges that this dissertation looks to overcome.

Chapter 3

Approach

This chapter explains in detail the proposed approach to solve the problem identified in chapter 1. There's a section that describes the experimental work done before the implementation, that led to the development of a first small prototype and the selection of Unity and Vuforia as the platform and framework for AR features. Next, all of the approach's implemented components and features are described, along with screenshots illustrating them. Finally, there's a section that enumerates major drawbacks and how they were overcome, justifying some design choices.

3.1 Introduction

As stated earlier, the proposed approach is based on a smartphone application (app), that takes advantage of the benefits of paper maps and overcomes their limitations, endowing them with dynamic virtual elements and information. Usage is centered (but not limited to) in exploring the paper map and the virtual information displayed on it. A paper map can give a wider depth of detail in various angles, something not easily attainable in a digital map on a small screen and does not rely on a constant data connection.

The user can also turn on a GPS service, running in background on the smartphone, that notifies him of a nearby site that may be interesting, even if the smartphone is on the user's pocket while touring the area. This gives a great layer of visibility to sites that could go frequently unnoticed. Kuikkaniemi et. al. stated the important role of ubiquitous media technologies in raising public visibility and awareness [14]. Upon launching for the first time, the user will be prompted to download the latest sites' information and multimedia content. This is done in an effort to reduce data usage to a minimum and not depend on a constant connection, that may not be always available. Although the app is focused on the *Águas Livres* aqueduct system, this concept can be extended and adapted to other cultural and historic heritage sites, in hopes for it to raise the interest of current tourists and captivate new ones to these sites.

As mentioned in section 1.1, this dissertation was developed in collaboration with Luís Marques. Luís provided most of the multimedia content and data related to the *Águas Livres* aqueduct, built the 3D models in collaboration with GEODRONE[1] and helped with on-site research arranging visits to the arches over the *Alcântara* valley, *Mãe de Água* and *Patriarcal*'s reservoir and *Loreto*'s underground gallery.

With the data available, drafts for the system and database schema were developed as well as interface mockups. Work in the concept started by conducting some experimental work in the AR field which resulted in a first small prototype. This prototype, that displayed 3D models of certain points of interest over a paper map, was shown informally to some potential users, who liked the concept and shown interest in further developments. The prototype laid the foundations of the app's implementation and development.

3.2 Experimental Work

Early before the implementation, some experimental work was done in the AR field of the mobile app to know how the Vuforia framework worked under various conditions. A Lisbon Yellow Bus tour map was used as the base of the image targets. In the end, the Unity platform was chosen for the AR component, over a native Android solution. These tests were done on a Google Nexus 5 smartphone running Android 5.0 Lollipop.

3.2.1 Teapots and multiple image targets

The first phase of testing was to know how Vuforia would handle displaying multiple objects when various image targets were on the camera's range. For this test, each image target had a 3D teapot model assigned to the origin of the axes, located on the center of the target. The map was sectioned in three different levels of depth of image targets:

- The first level was the whole map itself consisting of a single image target.
- The second level was the map split into four image targets, each one containing a quarter of the first level's target.
- The third level further split the map, with each image target containing a quarter of the second level's targets. This level had 16 image targets in total.

These 21 images were then uploaded to Vuforia's Target Manager[2], a tool used by the framework to create and manage target datasets, by identifying image features to be used for recognition and placement of virtual objects. Each picture had a maximum file size of 2MB, a limit imposed by the Target Manager and was 2500 pixels wide.

[1] http://www.geodrone.pt/

[2] https://developer.vuforia.com/target-manager

As mentioned in section 2.3.1, Vuforia can track up to five targets simultaneously, so how would it behave when more are present on the map? Furthermore, how can Vuforia handle overlapped image targets, if some are a fraction of another present on camera's field of view? Upon pointing the camera to specific regions and then to the whole map, it was clear that Vuforia had no trouble in handling overlapped images, but only displayed 5 teapots corresponding to the 5 most frequent image targets that it recognized (see figure 3.1). As there is no specific order of detection and a way to filter the different targets associated to the levels of depth puts a great amount of processing on the device, with little benefits, the idea of levels of depth was abandoned. Furthermore, splitting the map into different image targets, in an attempt to obtain a faster recognition, revealed to be more troublesome than advantageous further down the road, as stated in section 3.4.

Figure 3.1: First tests: multiple overlapped image target recognition using Vuforia

3.2.2 Model positioning and displaying

The next step was to position and display some models, other than the generic teapot, on the map. One goal was to position a previously georeferenced model in the map. This can be easily done if the corners of the image targets are also georeferenced and the model is built centered on the origin of the X and Z axes. Vuforia uses a local coordinate system for each target expressed in units that can be equal or different than the image's original width, with the origin of this system located on the center of the image. This means that, for example, the coordinates of a point located on the bottom-left of the image target will be negative on both axes. With all that taken into account, converting the global coordinates to the target's local coordinates can be done in a simple process.

It was now time to test some models and this is when the major problems using the native Android SDK began. Vuforia's Java SDK displays models using OpenGL ES (GLES), that only renders triangles and accepts basic matrix of geometric vertices, vertex normals and texture coordinates that correspond to a single texture file. This meant that no common file format such as OBJ or Collada could be used without some in-between conversion. A small parser was built in order to convert OBJ models to the GLES format.

Although this type of conversion can be swiftly done for vertices, the same cannot be said for textures as the process of merging all texture files into one and reassigning them to their polygon may vary from model to model. The results were not very satisfactory, as because of redundant information of some more detailed models (such as the ones that were built initially using quads) extra processing power was required, draining the battery at alarming rates and slowing down the performance, even though the tested models had a low polygon count. Adding to that, the extra work required to adapt the texture on the models could take too much of development time. Vuforia's documentation on placing 3D models on Android SDK is very poor, unlike its Unity extension counterpart. Search for an alternative was a necessity.

Provided that Unity gives full support out of the box for most common 3D models file types, including Collada, OBJ and FBX and direct export to Android and iOS devices, a test with the Vuforia extension was run on that platform. And not only the models were successfully imported, they displayed correctly and no massive battery drain or slowdowns caused by extra processing were verified.

At this point, development switched from native Android to the Unity platform, coming up with a small prototype (see figure 3.2) that, when pointed to a Lisbon Yellow Bus plan, displays 3D models of some important Lisbon buildings. This small prototype was the foundation of the AR component of the mobile app.

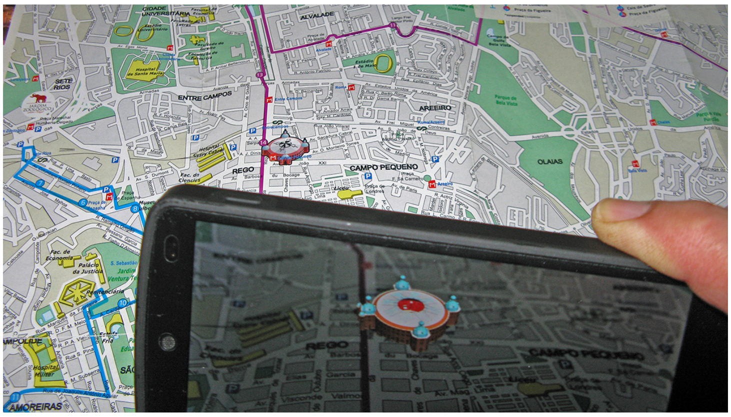


Figure 3.2: *Campo Pequeno* 3D model (4161 polygons) displayed over a Lisbon Map

3.3 System description

This section describes in detail the system, with each subsections focusing on its major components. The last subsection explains in detail the webserver. Due to some issues that arose during the development, the smartphone app had to be split into two, that communicate with each other. The reason for this split is explained in section 3.4. Henceforth, for the rest of this document each app will have a distinct name, introduced in their respective subsection, and the whole system will be dubbed **Aqueduct**.

3.3.1 Augmented Paper Map

The AR component of the system is an app, dubbed **Aqueduct AR**, that relies on a paper map recognized using the Vuforia AR framework powered by the Unity platform. The "Official Lisbon Plan" (figure 3.3) was used as the base map. A portion of the map was inserted in the Vuforia Target Manager. Although the paper map version used is from 2016, due to great similarities with the 2014 and 2015 maps, these versions are also recognized, though not immediately, and therefore can also be used. Vuforia takes less than 10 seconds to recognize these versions, provided there exists good lighting conditions.

Figure 3.3: 2016 edition of the Official Lisbon Plan paper map
The lit portion of the map was used as the Image Target, although due to big similarities the top left area of the map also displays virtual objects when viewed with the app

Upon recognition, the app places various virtual 3D objects on the map. Elements may be filtered on the interface according to their type. Figure 3.4 depicts the user interface. The user can view on the map:

- 3D representations of real sites related to the *Águas Livres* aqueduct system, which can be inspected in detail upon touch (detail view, as seen in figure 3.6d). Additional content can be accessed as seen in subsection 3.3.2. 3D models have an orange base / overlay in order to better distinguish them from the map, being that some also have an orange wall when they're against another building's wall.

  Additionally, the user can swap the 3D models with 2D points. This mode improves map readability, as 3D models may reduce it, as stated by Kuikkaniemi et. al. [15]. In this mode, it's possible to highlight 4 different type of sites: the

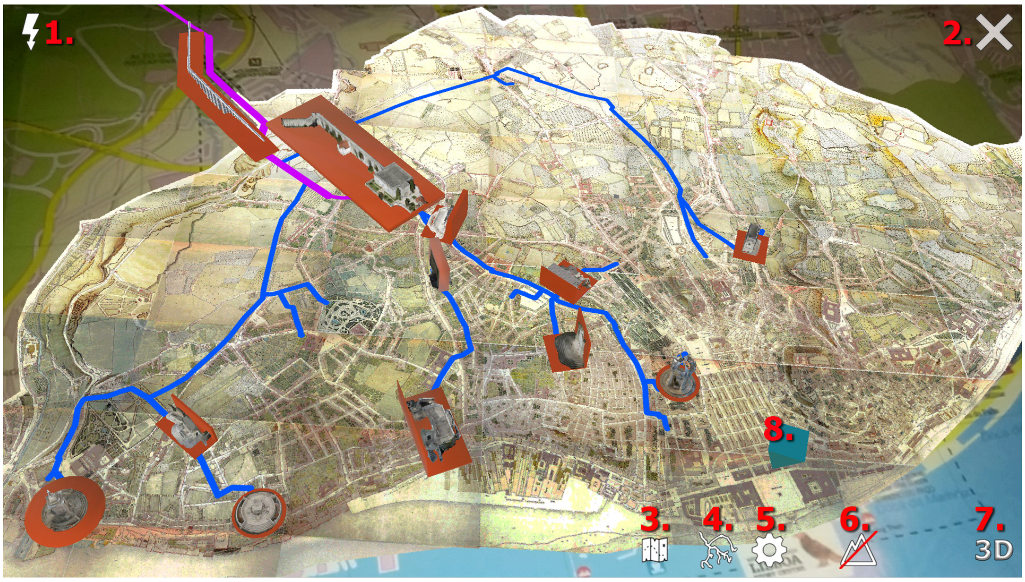


Figure 3.4: Overview of the camera view, with the cartography, pathway, 3D models and location marker on the map
Description of the interface: 1. Flash toggle, 2. Close map view, 3. Cartography toggle, 4. Pathway toggle, 5. Pathway settings, 6. DTM toggle (off in the image), 7. 3D/2D mode switch, 8. Location marker

aqueduct arches, reservoirs, fountains and a special type of fountains that were displaced from their original position (figure 3.6c).

In detail view (after touching one of the sites), the user can rotate and pinch to zoom the model in order to inspect it and look at its details (figure 3.6d). Another detail view was experimented: instead of taking the user to a different screen, where he could manipulate the model, the selected model would grow larger over the map (hiding the others in the process) and then the user could inspect it, by approaching the smartphone and rotate the paper map or view from a different angle. This type of detail view wasn't appealing to the users in the early evaluation and as such, was scrapped. More information can be found on chapter 4.

- Pathway of the aqueduct's network, where the user can highlight the underground, surface or visitable paths (figure 3.6b) or view an animation (image sequence) of the water flow. Three different colors are used: pink for the aqueduct's main pathway, blue for the pathway ramifications (galleries) and orange for the parts selected by the user. This is an example of a selective view of elements that cover vast areas of the map and how AR can be used to visualize hidden infrastructures [29].

- A 19th century cartography of Lisbon (figures 3.5 and 3.6a), made by portuguese mathematician General Filipe Folque, where we can see the rapid expansion that the city underwent since the aqueduct was built. Touching the cartography will take the user to a view, where he can navigate it as a digital map. This represents an example of overlapping different map layouts, with different content and possibly from different time periods.

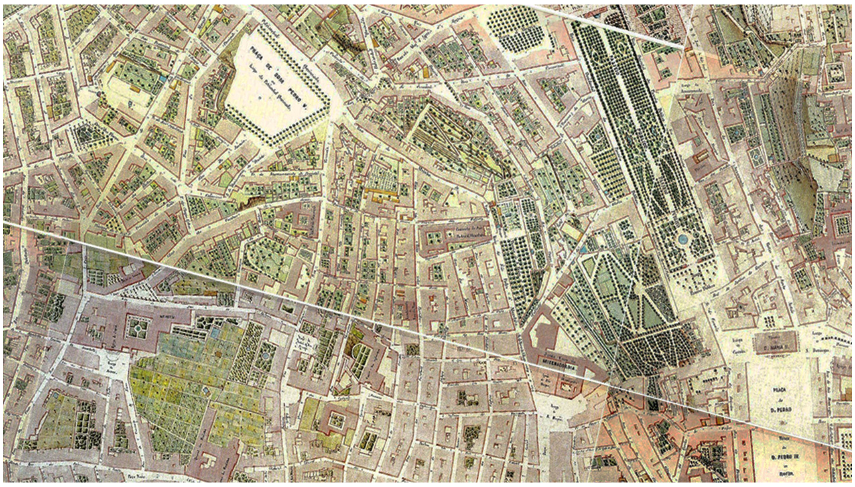


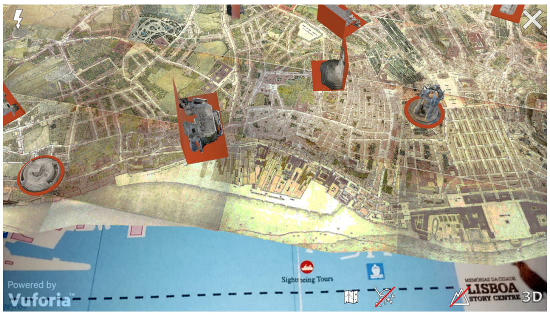
Figure 3.5: Part of Lisbon's downtown in Filipe Folque's cartography

- A Digital Terrain Model (DTM) of the city of Lisbon, colored in a 10 meter range elevation quota, where the user can better understand the aqueduct's pathway in relation to the terrain with a 3D representation of the pathway. The DTM can be opaque (figure 3.6e), allowing only the surface parts of the pathway to be visible or translucent (figure 3.6f), where the underground parts and the map are visible too.
- If the user is within the map's boundaries, a marker is placed on the paper mark indicating the user's current location, assisting in retrieving contextual spatial information (be it printed or overlaid), such as nearest historic sites. This is possible by matching the global location coordinates with the Image Target's local coordinate system [3].

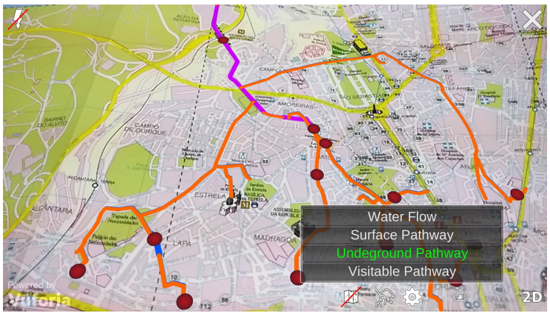
User preference of which elements should be present on the map is stored between app usages. The user can also manually focus the camera, by touching anywhere on the screen, that isn't a button or a virtual object and turn on the smartphone's flashlight (if available) to help the exploration in low light conditions.

3.3.2 Multimedia Content

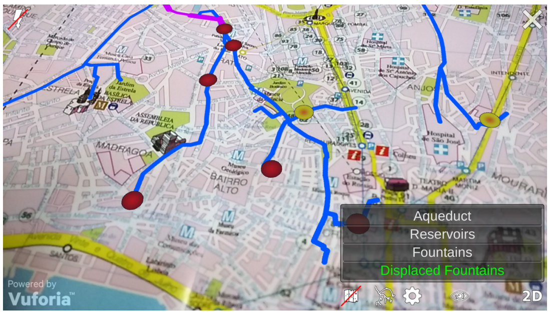
Multimedia content and the location-aware service (section 3.3.3) are in a separate app called **Aqueduct GPS**. This app can be launched from Aqueduct AR directly to the selected element, or standalone. It allows the user to browse a list of cultural / historic sites, including the ones that aren't present on Aqueduct AR as they lack a 3D representation (figure 3.7b). Each site has a small text description that emphasizes its building date, historic role and eventual changes that it suffered. Information is available in Portuguese and English, with the possibility of adding more languages on demand. This information



(a) 3D models and cartography overlapped on the map

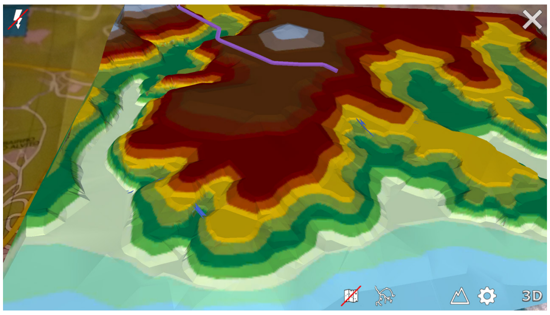


(b) Underground pathway highlighted (blinking in orange)

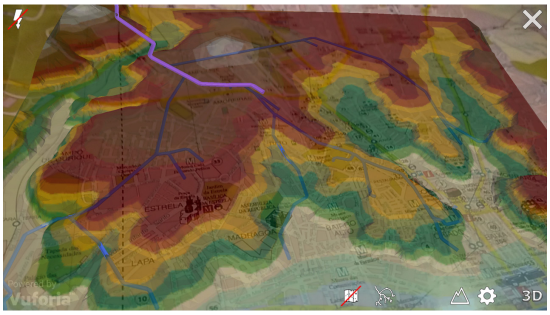


(c) Displaced fountains highlighted (blinking in yellow)

(d) *Janelas Verdes* fountain in detail view



(e) Opaque DTM, allowing only the surface pathway to be visible



(f) DTM with transparency, making the underground pathway visible

Figure 3.6: Various screenshots of the Augmented Reality features of Aqueduct AR

In figure 3.6d, top right buttons takes the user to the fountain's multimedia content view or back into the paper map camera view.

may be accompanied by pictures (historic and recent, as seen in figure 3.7e), videos and a 3D representation (as seen in subsection 3.3.1), when available. Regarding cultural sites that require a fee for visiting and / or have a specific opening schedule, that information is also provided (figure 3.7d). Multimedia content is available through a web server. This allows the continued addition of updated information, multimedia content and even the addition of new sites. The system is designed to be used on situations where an immediate data connection may not be available (be that because of no network coverage, lack of WiFi hotspots or very limited data plan like in roaming networks). For that reason, data is cached locally and the user can always update the contents on demand. Further details on the web server will be described in subsection 3.3.4. Finally, a digital map with all site locations and pathway was added after user feedback from early evaluations (see figure 3.7c and chapter 4).

3.3.3 Location-aware service

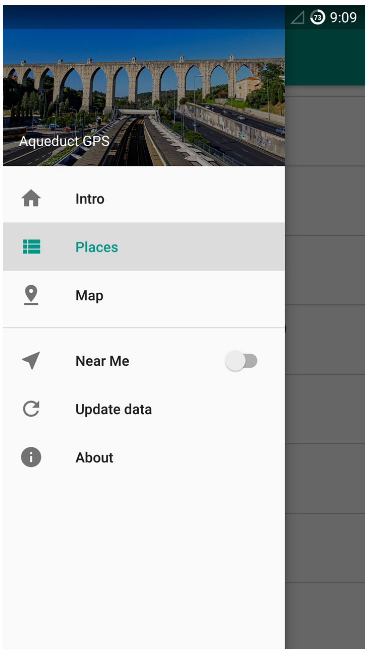
Aside placing a marker on the paper map, Aqueduct GPS has a notification service that the user can activate, called "Near me". This service triggers a notification when the current location falls within a site's 150 meter radius, even if the phone is in the user's pocket. That notification, when touched, can provide more information or start a navigation app that directs the user towards the site (figure 3.7f). Location is calculated using the smartphone built-in GPS sensors which are more appropriate for wide areas [5]. "Near me" is an effort to minimize the overlook of less known sites on a normal sightseeing trip (for example, a user might be notified about an underground gallery of the aqueduct, that passes under the street he's currently in, and view photographs of that site).

3.3.4 Content web server

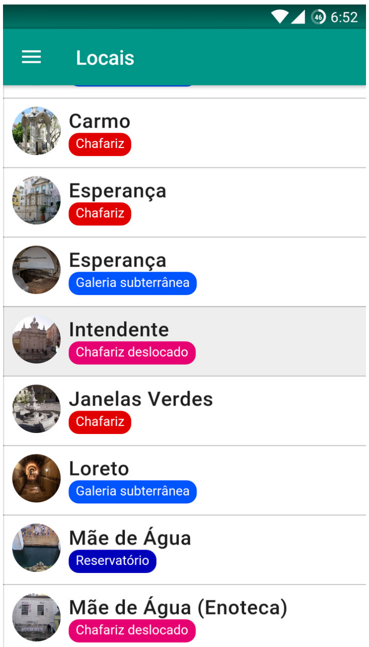
The web server is a very simple content hub, where the latest information and multimedia contents are stored. Aqueduct GPS downloads such data from the webserver via a REST API, that communicates with a MySQL database, whose diagram can be seen in figure 3.8.

REST API is implemented through PHP, which executes specific database queries and returns data processed in a JSON file format, that in turn, will be parsed by the app. Given the prototype nature of this implementation, no backend interface was developed (data must be inserted into the database manually and files must be uploaded through FTP) and only the necessary API calls were implemented. However, both the database structure and the API implementation are flexible, giving the possibility to be easily extended. Calls implemented are as follows:

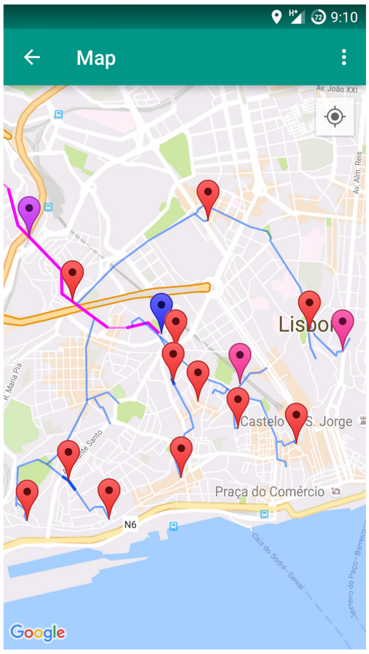
- `GET places.php` - Lists all cultural and historic sites available, their type, coordinates, their description text in all available languages, and technical fields used internally by the app.



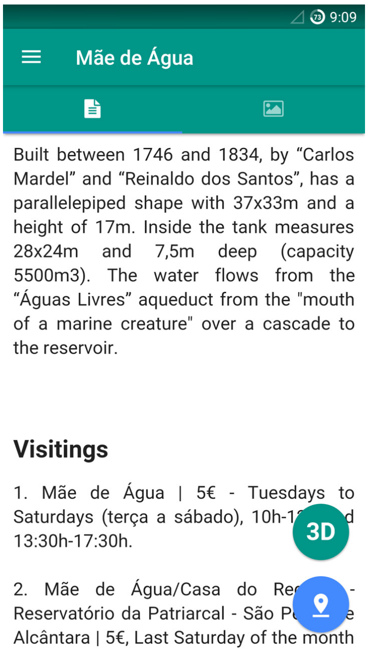
(a) Drawer menu of the multimedia & GPS app



(b) List of sites with their type

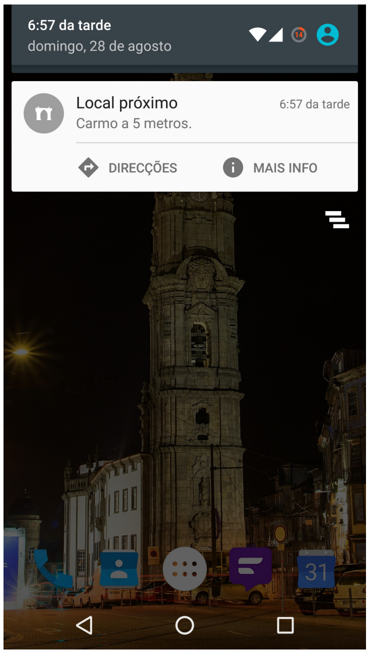


(c) Digital map



(d) Text and visits views

(e) Picture gallery



(f) Notification of the "Near me" GPS service

Figure 3.7: Screenshots of some of the multimedia and location features of Aqueduct GPS

Figure 3.7d shows an historic description of the *Mãe de Água*'s reservoir, as well information about fees and opening schedule. Touching on the marine floating button will take the user to Aqueduct AR, where he can see the 3D representation in detail. This button is only available when such representation exists. The blue button will center the digital map on the site's location if it's a building or will show the whole extension of the pathway if it's an underground gallery.

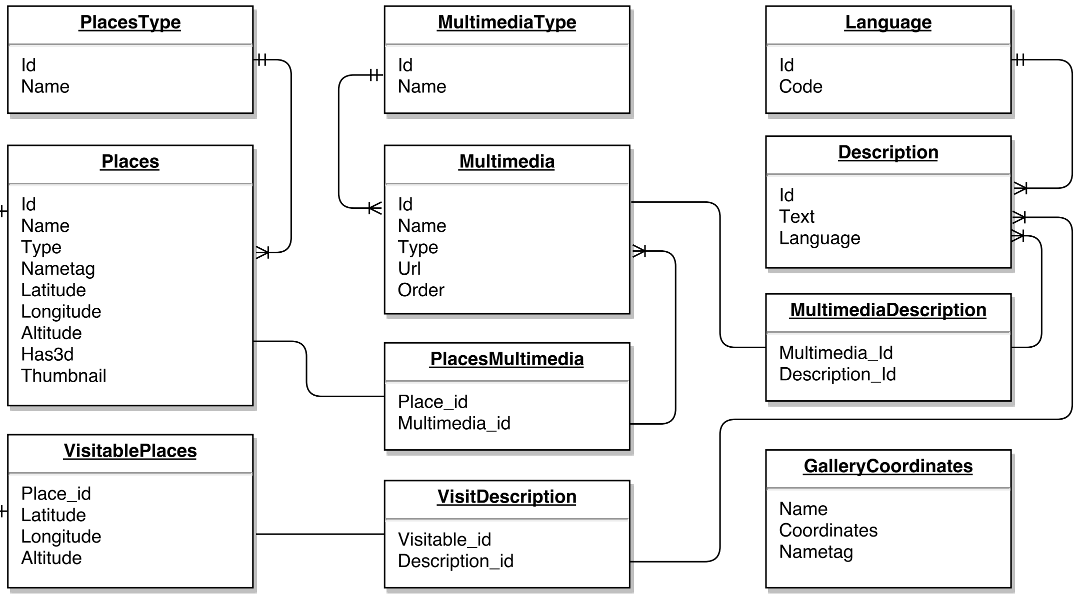


Figure 3.8: Database diagram

- `GET files.php` - Lists all multimedia files available for download. Used by the app file downloader.

- `GET multimedia.php?type=TYPE` - Lists all multimedia content available that is linked to a specific cultural and historic site and their caption (if available), in all available languages. This call in particular has a mandatory `TYPE` parameter that returns the list associated to that type. As there were only two types of files available, two API calls were implemented:

  `GET multimedia.php?type=photo` - Returns a list of all pictures available.

  `GET multimedia.php?type=video` - Returns a list of all videos available.

- `GET visitables.php` - Lists schedule and price information about all cultural and historic sites that are open to visits.

- `GET pathways.php` - Special API that returns a set of coordinates for each specific pathway of the aqueduct system. Used internally by the app for digital map and GPS service.

3.4 Overcoming drawbacks

These sections explains some design choices of the implementation, as well major drawbacks that were encountered during development.

3.4.1 Digital Terrain Model issues

The DTM was provided in an ARCGIS format, which has no direct conversion to a format supported by Unity. The only 3D formats that ARCGIS allowed to export the DTM were Collada and VRML. With Unity only supporting the first, it seemed to be the most direct approach, but as the DTM had too much information, ARCGIS would just abort the conversion due to "out of memory" errors. Many attempts were made with different elevation intervals (5, 10 and 20 meters), all returning fruitless results and taking up too much time off development. An alternate export method was needed. Upon research, it was found that Blender[3] had an extension, that allowed imports of models in the VRML format[4]. After some trial and error, a DTM with a 10 meter elevation interval in a VRML format was successfully exported and afterwards imported to Blender. It was now possible to export the terrain model in a format supported by Unity. As the pathway dataset (in Google Earth's KML format) didn't have any elevation data, it couldn't be used for displaying the pathway underground and at surface. As such, the 3D pathway had to be done from scratch, based on the KML data, and adapted to the DTM, giving an approximate overview to the reality.

3.4.2 3D Models

The original provided 3D models had a high polygon count (one of the highest having almost 214000 polygons) and weren't centered in the origin of the 3D axes. Although the high polygon count meant more depth of detail, it weighted on the app's size and performance, as Aqueduct AR took over 150MB of space and performed very poorly on mid-range smartphones, to the point of closing unexpectedly due to "out of memory" errors. Such depth of detail isn't needed for the propose of displaying the model on a paper map, but would be wise to maintain a acceptable degree of quality for the detail view, as reducing it drastically would defeat the propose of this view. Also, not being centered in the origin of the 3D axes caused the touch rotation to be rather clunky, with the model rotating in orbit of an invisible axis rather than on itself. All models were, one by one, centered to the origin and had their polygon count greatly reduced to a degree where they were very lighter, but only lost a negligible level of quality. This process was done with Autodesk Maya[5]. After this, the biggest model in terms of polygon count had just over 47000 polygons, enabling the app to run smoothly even on mid-range smartphones. Figure 3.9 shows a comparison between the original model of the *Esperança* fountain and a lighter version of the same model, with less than a quarter of its original number of polygons.

[3] https://www.blender.org/

[4] https://sourceforge.net/projects/vrml97import/

[5] http://www.autodesk.com/products/maya

(a) 33716 polygons (b) 7969 polygons

Figure 3.9: In-app comparison between the original model of the *Esperança* fountain (3.9a) and the cut model (3.9b)

3.4.3 Splitting the app

Initially, the implementation was to be done only in one app, which eventually became Aqueduct AR. The detailed model view had the description and multimedia features integrated in the interface mockup, as shown in figure 3.10. As the development progressed, the GUI tools provided by Unity didn't allow the creation of a good looking interface, without time-consuming design from scratch. As such, an alternative was sought and it came in form of an embedded HTML5 webview, that could emulate a solid and less time-consuming interface. However, performance of the webview in Unity turned out to be poor with great slowdowns, even when it was the only element present on screen, rendering it practically unusable. Parallel to this problem, was the issue of integrating the GPS service with Aqueduct AR. As Unity is a game-oriented platform, it has no native support for some system-specific features such as Android services. In this case, the tailored code must be built on the native Android SDK (e.g. Android Studio) and then exported in the form of a Java plugin to Unity [33]. The plugin was made, exported and integrated but, for an unknown reason, neither the service or the debug worked (which was complex to do, as two different programming languages were being used). At this point, and given the prototype nature of this implementation, putting the multimedia content and the GPS service in a standalone native Android app seemed to be a more feasible solution in terms of time-consumption and easiness of development. Aqueduct AR and the multimedia / GPS app (initially dubbed the "native" app, due to being developed using the native Android SDK and later, Aqueduct GPS) communicate with each other via system messages (Intents) and the fast transition between each other revealed to be the most viable solution for the sake of time constraints. This is the main reason for the existence of two apps that depend on each other instead of a single one.

3.4.4 Various Image Targets vs. Single Image Target

As mentioned in section 3.2, initially the map was sectioned into multiple image targets, in order to understand how Vuforia would handle various image targets in range. In an

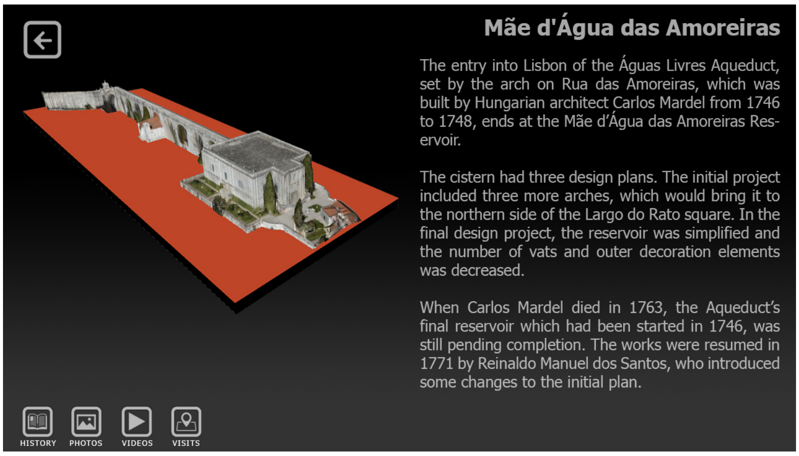


Figure 3.10: Interface mockup of the detail view before the app split

effort to allow the usage of more features for faster recognition, the area where the virtual objects were to be placed was sectioned into 4 separate image targets, each corresponding to a quadrant of the area. Although 3D models of sites were put on their corresponding image target, putting the cartography, pathway and the DTM on the map presented a problem as they covered all four targets. Placing these elements in one of the 4 targets, or sectioning into the 4 targets seemed both a viable solution, until they were experimented with the actual paper map. In the first case, the cartography and the pathway became distorted outside the image target's area, while on the second case the section cutting points were clearly visible. Overlapping a fifth image target covering the whole area was tested, but it yielded poor results as it slowed the recognition of the image targets. As a single image target was the viable solution for the virtual objects that covered all the map's area, all 3D models that remained on the sectioned targets were moved to the single target that covered the whole area and the sectioned targets were removed from Vuforia's dataset. Testing of the single image target approach yielded some interesting results. Even though the image inserted on the Vuforia Target Manager had theoretically less features (as it was an image of the whole area with just 2500 pixels wide as opposed to 4 quarters of the same area but each 2500 pixels wide, due to Vuforia's limitations), this single image target was recognized very much faster, even in very low light conditions. With these positive results in mind and the simplification for placing the larger virtual objects, a single image target approach was adopted, also allowing for a simple placement on the map of marker identifying the user's location, a feature added late in development.

3.5 Conclusion

This chapter described Aqueduct, the proposed approach, and presented its features, technical details and the drawbacks that arose during its development, justifying some of the design choices that were made. The app was submitted to various user evaluation moments as seen in the next chapter.

Chapter 4

Evaluation

Evaluation by potential users is an important role in a new kind of approach, as it has a crucial part deciding whether the concept is on the right direction or needs to be rethought. This chapter details the three evaluation moments that Aqueduct underwent: one during its development, other after the end where it was compared to other heritage-related apps and finally a real on-site situation usage. User feedback is presented and analyzed in detail.

4.1 Early Evaluation

During the development, an early evaluation was conducted in order to understand user reaction to this concept and their preferences. Some features were not yet available (like the DTM) or were still being finalized (GPS service, which wasn't tested on-site). For this purpose, two different applications were used: one that uses the paper map in combination with the smartphone (Aqueduct, the proposed approach, consisting of Aqueduct AR and Aqueduct GPS) and another that only uses the smartphone with a digital map software (henceforth called Aqueduct Digital). Except for the 3D representation on the map (replaced by markers), this version has the same features of Aqueduct. Figure 4.1 depicts the main screen of Aqueduct Digital. Two types of 3D model detail views were tested for the AR app of Aqueduct, in order to know which one appealed more.

This user study was conduced with 15 voluntary users (6 male and 9 female) with ages between 21 and 78 years ($\bar{x} = 45$, $\sigma = 19.53$).

4.1.1 Methodology

Before each test session, participants were briefed about the test and the applications they would be testing. Then, users were asked to complete a set of tasks twice, one

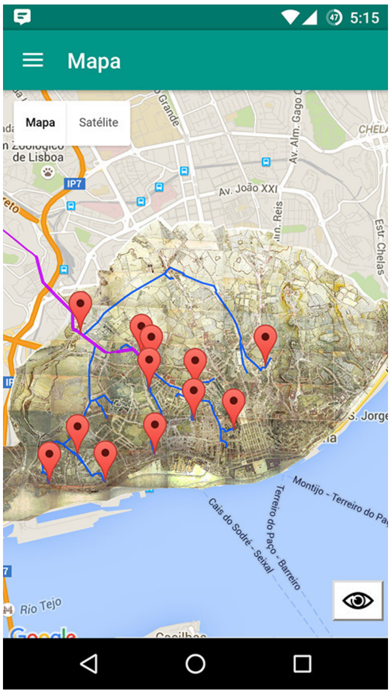


Figure 4.1: Main screen of Aqueduct Digital showing the pathway, cartography and the sites represented by markers

per approach. A within-subject experimental design was used to test the two different approaches and the sequence of use of the different apps (Aqueduct, Aqueduct Digital) was counterbalanced to minimize learning effects.

The set of tasks consisted in choosing sites, inspecting their 3D representations and associated information, viewing the aqueduct system pathway in order to understand the connection between the different sites and finally observing the 19th century cartography overlapped with the current map. At the end of each test session, users were asked to answer a questionnaire to evaluate their experience with the apps.

The questionnaire started by asking users' age and gender. Next, users were asked to rate a set of statements for each one of the two apps, using a five-point Likert-type scale, which ranged from disagree (1) to agree (5). Then, users were asked about which variant of the app they would prefer in different situations. Finally, users could express any further suggestions and comments.

4.1.2 Results

Regarding the overall features (figure 4.2), users generally agreed that overlapping the pathway helped them to understand the connection between places ($\bar{x} = 4.47$, $\sigma = 0.52$) and they found the possibility of overlapping historic cartography on the map interesting ($\bar{x} = 4.6$, $\sigma = 0.63$).

When compared to Aqueduct (figure 4.3), users found that Aqueduct Digital was easier to use ($\bar{x} = 4.47$ of Digital vs. $\bar{x} = 4.13$ of the proposed approach, with both σ

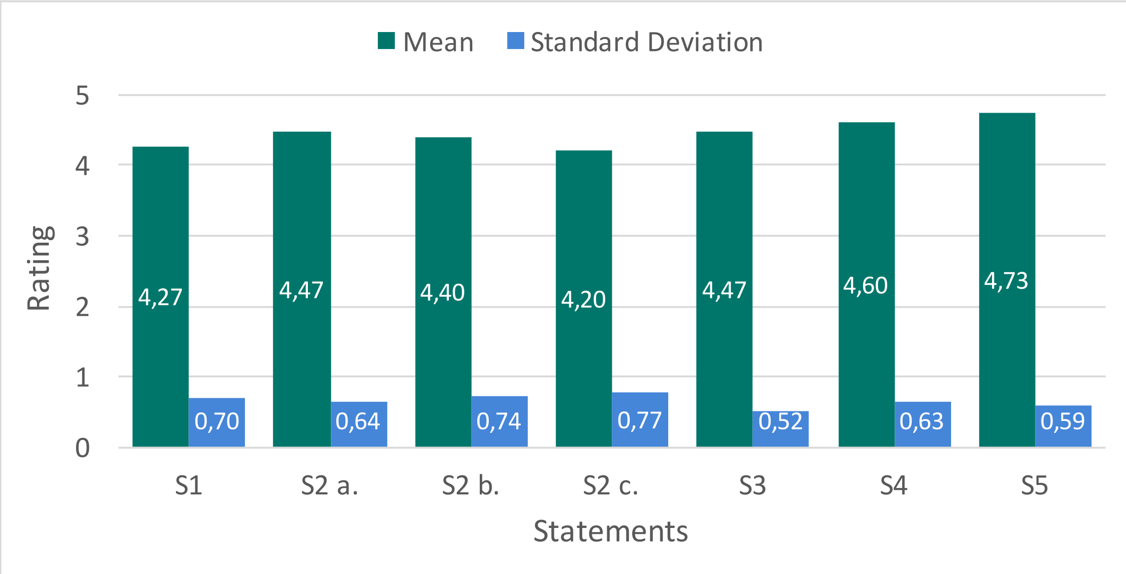
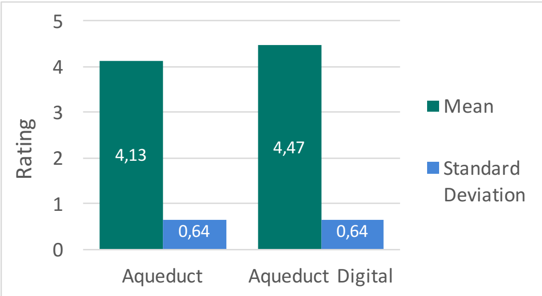


Figure 4.2: Early evaluation: questionnaire results of Likert-type scale statements

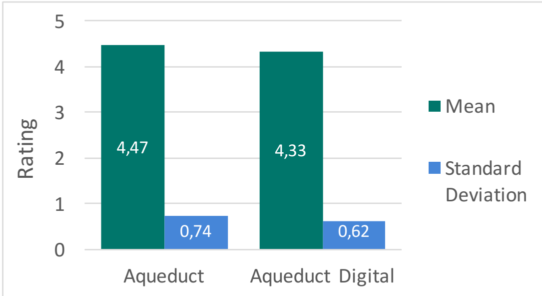
Table 4.1: Statement label key for figure 4.2 chart

	Statements
S1	Multimedia information associated with each site helps to understand its historic role
S2	The indication of the following information associated with a historic site is helpful: a. Location b. Opening hours c. Visiting price
S3	Viewing the pathway on the map helps you understand the connection between the various locations
S4	The possibility of overlapping historical cartography on the map is interesting
S5	3D representations of the sites on the map are an added value

= 0.64). Some users, of different ages, had difficulty using Aqueduct AR, mainly with choosing the correct button to activate the different pathway view options and with the manipulation of 3D models, being that some discovered how to do it, by accidentally swiping the screen. However, they found the paper map + smartphone combination (Aqueduct) more appealing to use, ($\bar{x}$ = 4.33, σ = 0.62 of Digital vs. $\bar{x}$ = 4.47, σ = 0.74 of Aqueduct) noting that it gives a better overview of the city and detailed view of the sites (through their 3D representation) and helps them to plan and choose which places they want to visit. 3D representations of the sites on the map were unanimously considered an added value ($\bar{x}$ = 4.73, σ = 0.59). One user noted that the paper map approach *"encourages, for example, children and young people to [visit] historic areas"* for its use of virtual 3D objects. Issues risen by the users were related to the AR's app interface and the impractical use of the paper map in some situations. This last issue met agreement



(a) This version is easy to use



(b) This version is appealing

Figure 4.3: Early evaluation: comparison of questionnaire results between the two versions

among users that Aqueduct AR is better suited for being used on a stable surface, like during a small break on a coffee table (73.3% preferred this approach on this situation), whether Aqueduct Digital does a better job for quick consulting while wandering around the city (gathering a consensual 86.7% of preferences). Micheel encountered the same problem during testing, as tourists found difficult to hold the map on one hand and the phone on the other [17]. As such, after this evaluation, a digital map was included, with locations of the sites and the aqueduct's pathway as shown in figure 3.7c. This is the only component of the app that requires a constant data connection, due to the current inability of providing offline areas for external applications by the Google Maps API.

As for the 3D detail views, users preferred the one where they could rotate and pinch to zoom the model, to the other where the model would grow bigger on the map. Some users failed to realize that they could inspect details by seeing the enlarged model from different angles and others complained informally that rotating the paper maps was very impractical.

An encouraging 73.3% of the users preferred the paper map + smartphone combination (Aqueduct) over the smartphone only with digital map (Aqueduct Digital) and would use Aqueduct if it was made available for an area they visited.

Finally, users were shown Aqueduct AR running on a 7.9 inch tablet and were asked informally if they preferred the app running on a larger screen. Although users did admitted that a larger screen would benefit viewing the virtual elements on the map and in detail mode, they were quick to point out that a tablet was very impractical to use while moving around, due to its dimensions and not being part of a user's regular inventory.

This evaluation was an important point in Aqueduct's development, as not only it showed promising results in the AR features, encouraging further development of this component, but also showed the need of a digital map (a feature not previously planned) as the paper map isn't suitable for all moments.

4.2 Urban Heritage Valuation Workshop

Shortly after the end of the development, a workshop in urban heritage valuation was organized by Luís Marques as part of his PhD. This workshop's goal was to evaluate four different smartphone applications, in the context of their role in cultural heritage awareness. Features ranged from basic AR display to information placed on a digital map, with some apps also having location-aware features. Of this four apps, three were commercially available and the fourth was Aqueduct.

4.2.1 Methodology

A single workshop session was held, where users were first briefed about its context, introduced to the apps being analyzed and then proceeded to analyze each app and its features. Regarding Aqueduct, users were asked at this point to view the different elements on the paper map and multimedia information. User interaction with Aqueduct was observed. Following this analysis, participants went to the nearby *Largo do Carmo* to experiment the location-based features of the apps. Finally, participants returned to the workshop briefing point for a overall discussion and answering an online questionnaire made by Luís. They rated their experience with each app in different aspects, using a five-point Likert-type scale, which ranged from 1 to 5. A total of 13 questionnaires were validated from 5 female and 8 male participants with ages ranging between 25 and 65 years (35-44 being the mode group).

4.2.2 Results

Participants discussed that 3D is an interesting feature, as it allowed observation of details that otherwise would be difficult to see in a 2D static photo. Some suggested that it would be interesting to have a 3D reconstitution of disappeared sites, with one participant mentioning the practically demolished *Muralha Fernandina* of Lisbon, while others suggested a past / present comparison of sites. There were mixed positions regarding the utility of 3D near the real site, with some considering the idea that 3D is only useful for a planning stage and not when we are seeing the real thing. However, others backed the idea of 3D being useful even near the real site, as it allowed to see some details without moving or enabling the user to view from perspectives otherwise difficult (such as details from above). Overall, participants agreed that 3D representations have potential for paper map applications, or bigger maps that are in exhibit on museums and even in the Virtual Reality field. One participant concluded that *"technology values cultural heritage. The problem is trying to sell it"*.

As for the questionnaires, the provided information revealed that Aqueduct had a higher mean than the overall app mean rating for each question (figure 4.4). Mean difference was lower in the Development aspects, but with Aqueduct coming higher than the overall mean. Highest mean rating came from the 2nd statement in the Quality

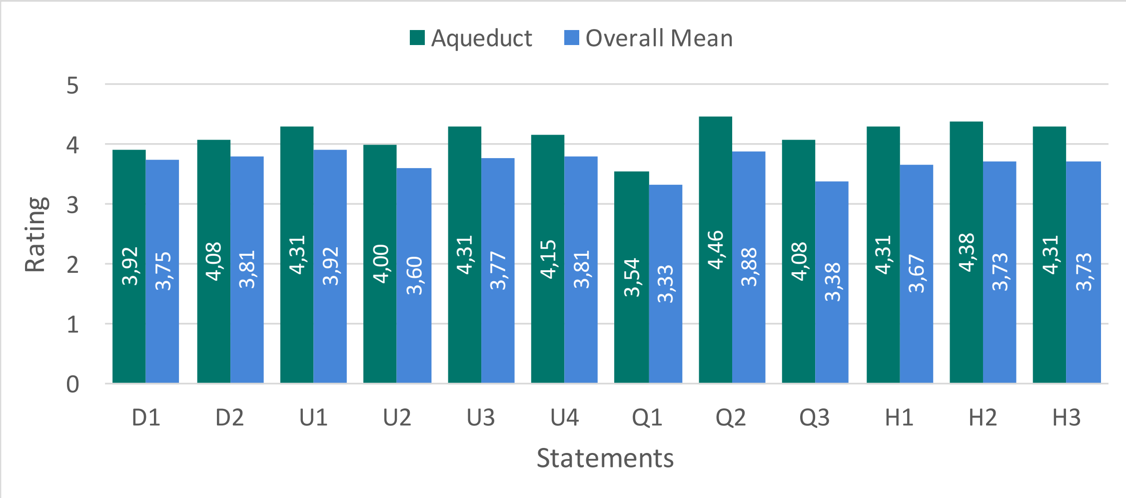


Figure 4.4: Workshop evaluation results, comparing Aqueduct's mean with the apps overall mean

Table 4.2: Statement label key for figure 4.4 chart

	Development Statements
D1	Classify the apps in relation to design (form and function) and aesthetics (visual appeal)
D2	Classify the apps considering the ease of use
	Usability Statements
U1	Classify your perception regarding the universe of potential users taking into account the availability in different languages and level of interest
U2	Classify the apps according to the capacity to engage the user
U3	Classify the apps according to the degree of user satisfaction and considering their initial expectations
U4	Classify the apps according to usefulness information for the user
	Quality Statements
Q1	Classify the apps according to the degree of reliability of the data (e.g. historical and relevance to the type of user)
Q2	Classify the apps in accordance with the potential of application to other heritage elements (e.g. Ancient Fernandina Wall or Lisbon 1755 pre-earthquake)
Q3	Classify the apps according the level of knowledge acquired relatively to the study object
	Heritage Appreciation Statements
H1	Classify the apps according to the potential dissemination of the heritage object
H2	Do you consider that the apps increase the value of the study object addressed to agents (e.g. tourists, local business, technicians, politicians)?
H3	Would you recommend the apps to other users to explore the heritage elements in study?

aspect, where users rated the app in accordance with the potential of application to other heritage elements ($\bar{x}$ = 4.46 of Aqueduct vs. $\bar{x}$ = 3.88 overall). This result meets the suggestion stated in the discussion, that 3D representations are an interesting feature and have potential applications in various situations. Finally, the aspect with the highest mean difference was the Heritage Application: participants agreed that Aqueduct has a good potential dissemination ($\bar{x}$ = 4.31 vs. $\bar{x}$ = 3.67) and value of study ($\bar{x}$ = 4.38 vs. $\bar{x}$ = 3.73) of the heritage object and would recommend the app to other users ($\bar{x}$ = 4.31 vs. $\bar{x}$ = 3.73).

This workshop showed the potential of Aqueduct in its prototype nature when compared with other commercially available apps. Discussion gave ideas for more AR applications that can be explored in future works.

4.3 On-Site Evaluation

Finally, an evaluation was conducted in order to test Aqueduct's behavior and usability in a real situation. All features of the system were tested and rated by 13 voluntary users (4 male and 9 female) with ages between 21 and 61 ($\bar{x}$ = 43.23, σ = 14.23).

4.3.1 Methodology

Three test sessions were performed with 4, 6 and 3 persons, respectively. Participants gathered in a meeting point near the *Mãe de Água*'s reservoir where they were briefed about the tests and features of the system they would be experimenting. They were presented a route that started and ended at the meeting point, with the *Principe Real*'s garden acting as a midway point.

This route's goal was to test "Near me" service and its role in raising awareness of not so apparent or hidden sites, as well as introducing sites to participants. The route had three fountains, three underground galleries, and two reservoirs nearby. Participants had freedom of deviating from a simple "*Mãe de Água* to *Principe Real* and return" route, in a effort to discover less known points, mainly the *Arco de São Mamede*'s fountain and the surface part of the *Esperança*'s gallery. As the three sessions discovered these two points, the route taken can be summarized as the one in figure 4.5.

Uncommon to all sessions was the moment where participants experimented Aqueduct AR with the paper map (figure 4.6): While session 2 used Aqueduct AR before beginning of the route, sessions 1 and 3 used the app midway into the test, in an effort to learn potential differences in the user's reception of the AR app. After the end of each session, participants were asked to answer two questionnaires to rate their experience with Aqueduct. One questionnaire focused on the AR and Multimedia features, while the other focused on the GPS capabilities.

Questionnaire started by asking users' age and gender. Next, users were asked to rate a set of statements for each feature, using a five-point Likert-type scale, which ranged from

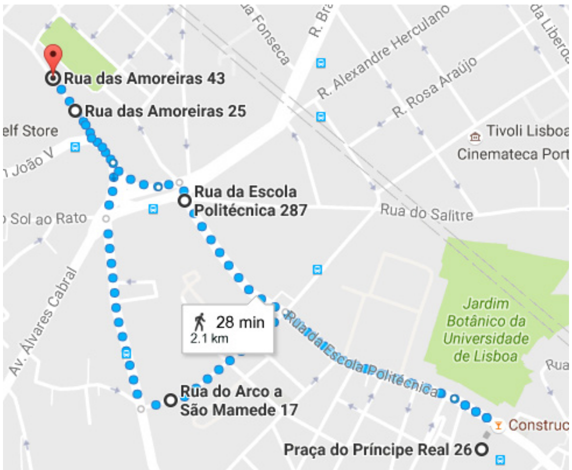


Figure 4.5: Common route taken by all on-site test sessions

disagree (1) to agree (5). Some statements returned from the early evaluation (section 4.1) questionnaire. Finally, users could express any further suggestions, comments and the app / service advantages or disadvantages they thought important to point out.

Figure 4.6: On-site evaluation: users testing the paper map AR features

4.3.2 Results

Feedback for the on-site evaluation was more positive than the early evaluation. Users again agreed that multimedia information helps to understand the sites' historic role ($\bar{x}$ = 4.62, σ = 0.51) and the presence of information such as location, opening hours and price (when applicable) was considered helpful (figure 4.7 depicts these results in detail). As for extra information, one user suggested that *"nearby bus [line] numbers [should be] mentioned [in the app]"*, indicating that public transport information is also relevant. Overall, users agreed that Aqueduct is easy to use ($\bar{x}$ = 4.46, σ = 0.52), appealing ($\bar{x}$ = 4.62, σ = 0.51) and helps not only planning a visit beforehand ($\bar{x}$ = 4.46, σ = 0.78), but also realizing details that could potentially go unnoticed ($\bar{x}$ = 4.69, σ = 0.48).

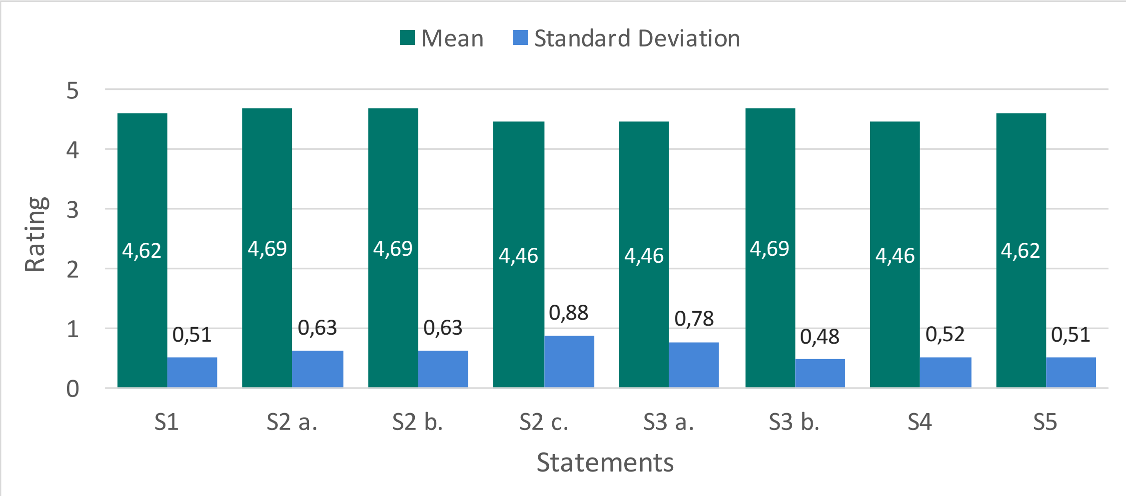


Figure 4.7: On-site evaluation: questionnaire results of Likert-type scale general statements

Table 4.3: Statement label key for figure 4.7 chart

	Statements
S1	Multimedia information associated with each site helps to understand its historic role
S2	The indication of the following information associated with a historic site is helpful: a. Location b. Opening hours c. Visiting price
S3	This system helps: a. Planning a visit beforehand b. Realizing details that would otherwise go unnoticed
S4	This system is easy to use
S5	This system is appealing

Figure 4.8 shows the results of statements oriented towards the AR features and the GPS service. Regarding the AR features, although 23.1% of the users admitted that they do not use a paper map while touring a city, they were very pleased with the AR features of Aqueduct (Aqueduct AR). They agreed that viewing the pathway on the map helped them to understand the connection between locations ($\bar{x}$ = 4.69, σ = 0.48), with some pointing it as one of the advantages of the app, and one in particular mentioning *"[that it allows us to] understand small details of the pathway that otherwise wouldn't be possible"*. This last idea is reinforced by the unanimous agreement that the representation of the terrain (through the digital terrain model and the 3D pathway) helps realizing the route of the aqueduct and direction of the water ($\bar{x}$ = 4.77, σ = 0.44). Users also considered the 3D representations of the site on the map an added value ($\bar{x}$ = 4.92, σ = 0.28) and

found interesting to overlap historic cartography on the map ($\bar{x} = 4.77$, $\sigma = 0.44$) - one user, after viewing the cartography, complained informally about the large portion that downtown Lisbon stole to river Tagus since the 19th century. But, the most consensual

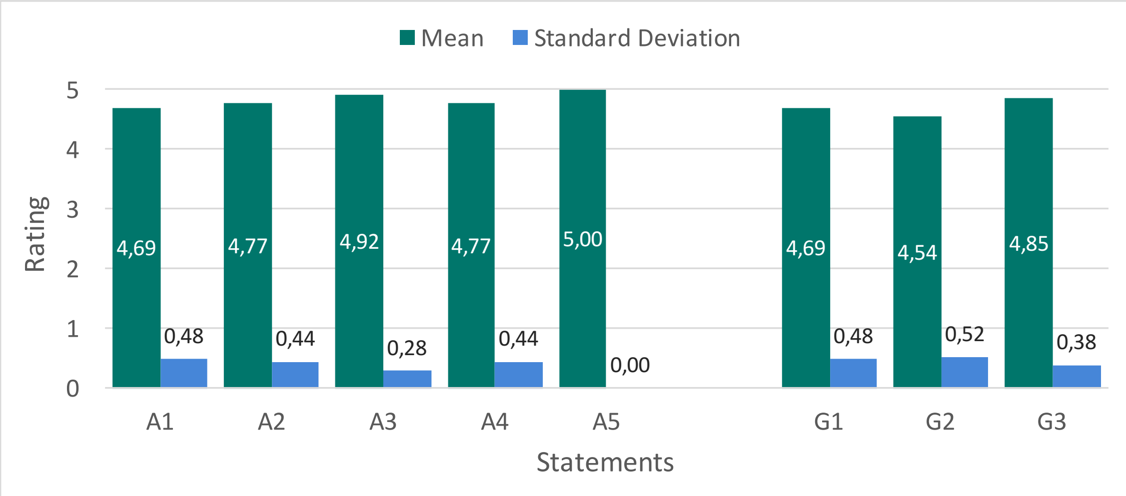


Figure 4.8: On-site evaluation: questionnaire results of AR and GPS service specific statements

Table 4.4: Statement label key for figure 4.8 chart

	AR Statements
A1	Viewing the pathway on the map helps you understand the connection between the various locations
A2	The possibility of overlapping historical cartography on the map is interesting
A3	3D representations of the sites on the map are an added value
A4	The representation of the terrain helps realizing the route of the aqueduct and direction of the water
A5	The indication of the user's current location on the map is useful
	GPS service Statements
G1	Notifications are useful
G2	Notifications are timely (i.e. notify in appropriated time and distances)
G3	Notifications help discovering less visible places

feature between the users, was the usefulness of indicating the user's current location on the map. It reunited a perfect mean rate of 5 ($\sigma = 0$), as some users pointed on-site to be a good alternative when digital maps aren't available. However, they also noted that moving around with a paper map is unpractical, reinforcing the idea that Aqueduct AR is better suited for a planning stage or to be used on a stable surface. The only major complain was about the heavy power usage, as using both the camera and 3D models puts a great weight on the smartphone's battery life.

Regarding the "Near me" service, while users liked the concept, some initially failed to understand that the service runs and notifies them while they're using other apps and even when they aren't using the smartphone at all. One group wandered through various side streets and found the *Monte Olivete*'s fountain thanks to this feature of Aqueduct. All groups successfully found both the *Arco de São Mamede*'s fountain and the surface part of the *Esperança*'s gallery, two sites that can be overlooked for being located in secondary side streets. Users agreed that the notifications are useful ($\bar{x}$ = 4.68, σ = 0.48), timely ($\bar{x}$ = 4.54, σ = 0.52) and, most of all, help discover lesser visible places ($\bar{x}$ = 4.85, σ = 0.38). This last statement was pointed as a main advantage by some users, as it allows to locate on-site lesser known locations, that otherwise would go unnoticed or remained unknown to them.

Overall, users pointed the helpfulness of Aqueduct regarding the propose of planning a visit and the *"easiness of making a guided visit without roaming through the sites"*. Participants liked the experience as, even though some knew Lisbon, they didn't know about some of the visited sites, their location and role. All users said they would use this app if it was made available for a city they visited, with some suggesting that it should be extended to other touristic points even at a national level and other emphasizing that *"official [touristic] entities should support these projects"*.

Although the moment of the AR experimentation was different between sessions, no significant differences were found, regarding the user's reception of Aqueduct AR. The positive results of this on-site evaluation further reinforced the potential of this concept and encourages future development, as there's a great receptivity by potential users.

Chapter 5

Conclusions

This final chapter reflects on the realized work and investigation of this dissertation and discusses the feedback given by the users' evaluation, as well as relevant behaviors observed during test sessions. Then, wraps up with recommendations and guidelines for cultural and historic heritage oriented applications and future work.

5.1 Conclusions

This dissertation presented Aqueduct, a smartphone application whose goal was to study new forms of exploration of cultural heritage, providing a different tour experience and raising public awareness of the various sites that made part of the *Águas Livres* aqueduct system in Lisbon. This experience combined paper maps with smartphones, presenting a new way to expand the capabilities of the former, using Augmented Reality technology to display virtual elements, that enhance the experience in exploring cultural and historic heritage sites, disclosing their correspondent details. A location-aware service is also part of this experience, as it helps the user discovering nearby places that may be of his interest and may otherwise go unnoticed. All of this requires only a regular smartphone and a widely available tour map, both common items of a tourist's inventory.

To evaluate the users' attitude and interaction, different test sessions were conducted as described in detail in chapter 4. Regarding the AR component, users liked the concept of virtual 3D objects over a paper map. Some were very surprised when they first saw such objects superimposed on a physical map and liked examining the details of 3D representations. Miyashita et al. had similar reactions from their users, while experimenting an AR concept of a museum guide for *Musée du Louvre* [19], further reinforcing the overall receptivity of Augmented Reality experiences by regular users. Participants of the different evaluation sessions unanimously agreed that the AR features helped them planning a visit to a place and, combined with the associated multimedia content, provided more information, eliminating the need of the traditional tourist pamphlets.

However, there are some issues regarding the usage of the paper map. Using a physical map and a smartphone while moving is difficult, as it's cumbersome for an user to hold and point a smartphone on one hand, while holding the map on the other [26] (even folded) and pay attention to its surroundings simultaneously. User feedback further reinforced the need of a stable surface, where the paper map can be placed and used without any inconvenience. A great example is using the paper map while resting on a garden's table, where the user, aware of his position by the marker placed on the map, can view the nearest sites and browser their information.

Users praised the "Near me" service for its usefulness in notifying the underground galleries whose location isn't always apparent and introducing them to sites that they didn't know existed, let alone being part of the aqueduct system. One user stated that *"was unaware of half of these location [before the briefing] and history of the aqueduct"*.

Overall study results were positive, with users approving and validating this concept and pointing its usefulness in helping to raise awareness (in this case) of the various sites related to the *Águas Livres* aqueduct. Users were unanimous in admitting that they would use an application like this, if it was available to the public, albeit needing a few graphical interface refinements, mainly in the AR component.

5.2 Recommendations and Future Work

As appealing as the paper map AR approach may be, it became evident that it's only comfortably appreciated on a stable surface. AR is better suited for a planning phase of a tour or on a small break, but it can provide a great experience and content for the user to know what he's exploring. Extra care should be taken not to overload the smartphone's screen with virtual objects and allow filtering what type of virtual objects the user desires to see at a given moment. The concept of an augmented paper map can be also extended to a large plane or scale model in exhibition, for example, in a museum of a historic fortified city, whose scale model can be used to recreate a 3D animation of a siege that the city underwent in the past.

3D representations of sites are an appealing aspect, as it allows users to inspect details that would otherwise be difficult to appreciate and should be also used, when possible, to recreate past versions of sites that underwent great changes or that disappeared. Content caching should be taken into consideration too, depending on the location and context. Users may have a limited or non existent internet connection / network coverage, so these applications should rely on a data connection as least as possible.

These recommendations should be taken in consideration for future development of historic and cultural heritage oriented applications.

As for Aqueduct in particular, future work passes firstly by optimizing the system and improving its interface (mainly the AR interface). The most crucial point of this optimization however, is to merge the two apps in one, as it was originally meant to be. More sites can be added, provided there's information for them and would be interesting to reconstitute demolished sites in 3D such as the *Passeio Público* fountain or the *São Bento*'s arch that was part of the *Esperança* gallery. Taking into consideration the users' input, more types of information should be added to the already existing sites on the app, such as accessibility and public transport information, official websites, among others. In relation to the location-aware features, the pervasiveness of Aqueduct can be improved, by sorting the list of sites by the nearest ones to the users and filtering of notifications, for example. It would be interesting to transpose the concept of the "Near me" service to the AR view, where nearby sites would be highlight, in order to alert the user of their proximity. Finally, the DTM and the 3D pathway have more potential to be explored; one of the many options is adding water animation in the future, helping the user to understand how the water was distributed in Lisbon by means of gravity. Having animations may increase the appeal and interest of younger audiences in this type of applications and in cultural and historic heritage overall.

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