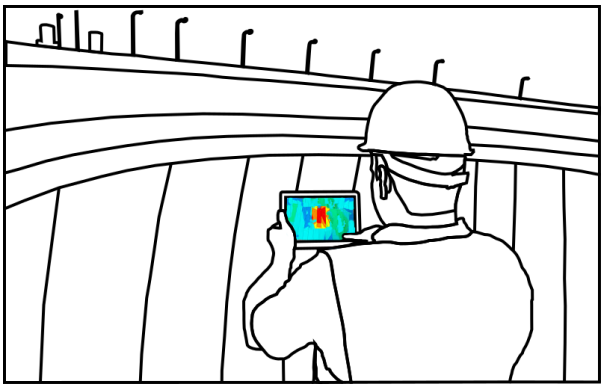
TÉCNICO LISBOA



Augmented Reality in Dam Monitoring

Nuno Filipe Verdelho Trindade

Thesis to obtain the Master of Science Degree in

Information Systems and Computer Engineering

Supervisors: Prof. Dr. Alfredo Manuel dos Santos Ferreira Júnior
Prof. Dr. Sérgio Bruno Martins de Oliveira

Examination Committee

Chairperson: Prof. Paolo Romano
Supervisor: Prof. Alfredo Manuel Dos Santos Ferreira Júnior
Member of the Committee: Prof. Maria Beatriz Carmo

November 2018

Dedicated to my Parents and to my Grandmother ”Gó”

Acknowledgments

I would like to express my sincere gratitude to Prof. Dr. Alfredo Ferreira of Instituto Superior Técnico (IST) at University of Lisbon (UL), for his knowledgeable orientation, without which this work would never have been possible. Prof. Ferreira continuous support allowed me to pursue this research to a level which exceeded all my expectations. His patience and friendship gave me encouragement and motivation to deal with difficulties and overcome obstacles.

I would like to thank Prof. Dr. Sérgio Martins Oliveira of the Concrete Dams Department (DBB) at National Laboratory for Civil Engineering (LNEC) for his invaluable orientation in the several stages of development. His help was crucial both in allowing me to understand how the important activities of dam observation and safety control are carried out at LNEC, in the field visits and also during the testing of the prototype.

I am extremely thankful to Prof. Dr. Sandra Gama of IST at UL, for her orientation. Her review and advice were fundamental for the development of this document.

I am very grateful to Eng.D. Maria João Henriques of DBB at LNEC for her help in the development of the prototype, namely at the Cabril Dam. Her teachings were of great importance for the completion of this project.

I am also grateful to Eng.D. Miguel Silva Rodrigues of DBB at LNEC, for his help at the Cabril Dam and valuable advice.

Furthermore, I would also like to thank LNEC for providing the means for field visits and testing the prototype and also the fantastic staff at the DBB for all their kindness and help.

Abstract

The construction industry has shown, over recent years, an increased interest in technologies such as Augmented Reality, as a mean to optimize its processes. This work explores the application of Augmented Reality to the inspection and monitoring of large Civil Engineering structures, namely of dams. It presents and discusses related work regarding the use of Augmented Reality in Engineering, Architecture and Construction. Furthermore, it proposes an approach to dam safety control, using Augmented Reality, focused on offering new visualization possibilities, that are not accessible through traditional means. In that scope it depicts the specification and development of a proof-of-concept prototype that allows the visualization, *in-situ*, of relevant structural health monitoring information, in an Augmented Reality environment. In particular, it offers Civil Engineers and Observation Technicians a mean to visualize, superimposed to the Cabril Dam (the case study covered by this project), the network of sensors situated in the downstream face and the interior of the structure, as well as the evolution of the values registered in each sensor. A preliminary evaluation, aimed at validating the proposed approach, shows that Augmented Reality technologies can be efficiently used in dam safety control.

Keywords: augmented reality, dam safety control, structural health monitoring, user interface

Resumo

A indústria da construção tem mostrado, ao longo dos anos mais recentes, um interesse crescente em tecnologias como a Realidade Aumentada, como meio para otimizar os seus processos. O presente trabalho explora a aplicação de Realidade Aumentada à inspeção e monitorização de grandes estruturas de Engenharia Civil, nomeadamente de barragens. Apresenta e discute trabalho relacionado relativo ao uso de Realidade Aumentada em Engenharia, Arquitetura e Construção. Além disso, propõe uma abordagem ao controlo da segurança de barragens, usando Realidade Aumentada, focada em oferecer novas possibilidades de visualização, não disponíveis através dos meios tradicionais. Nesse âmbito, descreve a especificação e desenvolvimento de um protótipo de prova-de-conceito dirigido à visualização, *in-situ*, de informação relevante, relativa a monitorização da saúde estrutural, num ambiente de Realidade Aumentada. Em particular, oferece a Engenheiros Civis e Técnicos de Observação, um meio para a visualização, sobreposta à Barragem do Cabril (o estudo de caso abrangido por este projeto), da rede de sensores situados no paramento de jusante e interior da estrutura, bem como a evolução dos valores registados em cada sensor. A avaliação preliminar, destinada a validar a abordagem proposta, mostra que as tecnologias de Realidade Aumentada podem ser aplicadas de forma eficiente ao controlo de segurança de barragens.

Palavras-chave: realidade aumentada, controlo de segurança de barragens, monitorização da saúde estrutural, interface de utilizador

Contents

List of Tables

List of Figures

List of Abbreviations

$2D$	Two-Dimensional
$3D$	Three-Dimensional
AEC	Architecture, Engineering, and Construction
AMI	Automatic Monitoring Instruments
APA	Portuguese Environment Agency / *Agência Portuguesa do Ambiente*
API	Application Program Interface
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer-aided Design
CSV	Comma-separated Values
DBB	Department of Concrete Dams / *Departamento de Barragens de Betão*
DTM	Digital Terrain Models
EDP	*Energias de Portugal*
$EN2$	National Road 2 / Estrada Nacional 2
FPD	Straight Plumbline / Fio de Prumo Direito
GIS	Geographic Information Systems
$GNSS$	Global Navigation Satellite Systems
GPS	Global Positioning System
HMD	Head Mounted Display
$HSDG$	High School Diploma Graduation
$HVAC$	Heating, Ventilation, and Air Conditioning
$INESC-ID$	*Instituto de Engenharia de Sistemas e Computadores, Investigação e Desenvolvimento*
IST	*Instituto Superior Técnico*
$Lic.$	*Licenciatura*
$LNEC$	National Laboratory for Civil Engineering / *Laboratório Nacional de Engenharia Civil*
MSc	Master Degree
MVC	Model–view–controller
PDT	Portable Data Terminals
PhD	Doctoral Degree
RSB	*Regulamento de Segurança de Barragens*

RTK	Real Time Kinematics
SDK	Software Development Kit
SHM	Structural Health Monitoring
TIR	Thermal Infrared
TST	Total Station Theodolite
UI	User Interface
UML	Unified Modeling Language
$USSD$	United States Society on Dams
$VIMMI$	Visualization and Intelligent Multimodal Interfaces
VPL	Visual Programming Lab
VR	Virtual Reality

Chapter 1

Introduction

In recent years, Augmented Reality (AR) technologies have been used in a multitude of scenarios and with distinct purposes, to provide relevant real-time information that enhances the interaction with the real world. The practical applications of AR have long exceeded the scope of entertainment and are progressively being introduced to the professional environment, namely in medicine, military, and tourism.

An area that registers increased interest in AR is Architecture, Engineering, and Construction (AEC). Here, AR applications have been studied or developed with such varied purposes as bridge maintenance, visualization of underground infrastructure, classification of pathology in architectural/historical heritage, structural design, inspection works or to visualize and verify Building Information Modeling (BIM) data in construction sites, among others. AR is also giving its first steps in the field of Structural Health Monitoring (SHM), which is the domain of Civil/Structural Engineering responsible for assessing the integrity and performance of structures, by means of detecting, characterizing and following the evolution of structural degradation.

1.1 Motivation

In the field of SHM, the opportunities offered by AR technologies are far from being fully exploited. Although the SHM area has been at the front line in what concerns data acquisition, namely through the widespread use of advanced sensing technologies, it continues to lack when it comes to *in-situ* visualization of structural health information. In the observation and safety control of dams, where this work focuses, that issue is especially pertinent, due to the typically large dimensions of dams and the difficulty in physically accessing certain areas.

The task of field visual inspection, which is an important part of the safety control of dams, requires that the inspector knows, among other information, where the different components of the dam are located. This includes the several types of sensors, in order to be able to both assess its condition and/or register its measured values (in cases where data logging and transmission are not automated).

Many of the technical challenges that, in the past, restricted the practical use of AR technologies in real-world environments have been lessened or even surpassed. One important issue was the inherent

lack of accuracy, especially in situations where the objects of the augmented environment were at a relatively long distance from the observer. This problem was tackled, in part, by the emergence of more capable AR software, Application Program Interfaces (API's), tracking methods and also, more importantly, by significant advances in the latest generations of hardware. Regarding this last aspect, it has been especially relevant, the dramatic increase in the definition and overall quality of cameras and sensors, as well as the speed and efficiency of graphical processors and even the planned integration of artificial intelligence coprocessors [1]. These progresses can be seen both in generic equipment like tablets and smartphones, and in "dedicated" platforms like Microsoft HoloLens[1]. Another relevant challenge associated with the use of AR in professional applications is the transmission and processing of large data sets, often required to produce precise and useful computer-generated images and other visual information. This aspect, that is increasingly relevant in an era where *big data* tends to be the standard, not the exception, is being handled by the emergence of faster mobile telecommunication technologies. Nevertheless, to take advantage of these technological advances, the use of efficient applications, that offer tangible benefits in the assistance offered to the user in the work environment, is imperative.

1.2 Objectives

The present work explores the use of AR technologies in vast exterior environments, namely in large Civil Engineering structures and analyses the role of AR technologies in the safety control of dams. Its main objective is the following:

To validate the applicability of AR technologies to the safety control of dams.

In that sense, it is focused on the opportunity of creating new observation paradigms, by offering visualization possibilities that would not be accessible using traditional tools.

As a proof of concept, the work includes the design and development of a prototype that can aid dam inspectors in the structural inspection of dams. This prototype runs on a tablet but was developed to be easily adaptable to dedicated AR Head Mounted Displays (HMD's) like the increasingly popular Microsoft HoloLens, Magic Leap One[2] or Facebook AR hardware, which was detailed in a recent patent application by Oculus Advanced Research Division[3].

The prototype allows the superimposition to the user's view of the real world, of relevant 3D information concerning the positioning and geometry of the network of sensors located inside the structure of dams and along its downstream face, as well as the visualization of structural monitoring data.

The work was developed in cooperation with *Laboratório Nacional de Engenharia Civil* (LNEC), and uses the Cabril Dam (Fig. 1.1) as a case study. This structure was suggested by LNEC as an ideal candidate to be used for this work and in particular for the validation of the application.

[1] Microsoft HoloLens, https://www.microsoft.com/en-us/hololens
[2] Magic Leap One, https://www.magicleap.com/
[3] Oculus patent, https://www.google.com/patents/US20170235143

(a) General View

(b) Downstream face of the structure

Figure 1.1: The Cabril Dam

It was together with LNEC technical staff that the requirements for the AR system were established. This was carried out through meetings and interviews with Engineers and Observation Technicians, as well as technical visits to the Cabril Dam, where LNEC's safety control activities were explained and demonstrated. It was also with their support that the evaluation of the prototype was carried out, both in what concerns its operation in the field and the suitability of the user interface.

1.3 Document structure

Apart from this introduction, the document presents, in Chapter 2 a theoretical background on dam monitoring and safety control, Virtual Reality (VR) and AR. Chapter 3 describes related work pertaining AR and more specifically the use of this type of technology in the AEC area. The specification of the prototype requirements is addressed in Chapter 4. In Chapter 5 of the document, the approach to the development of the prototype, is described. The evaluation of the prototype is shown in Chapter 6, comprising the field testing and user evaluation. In Chapter 7, the conclusions concerning this work are presented, including achievements and future work.

Chapter 2

Background

The meaning and relation between concepts such as dam safety control and SHM and also the way that these concepts are applied at LNEC are important to understand the underlying objectives of the development of the present work. To that extent, it is also relevant to realize how AR evolved over time, always in close connection with VR, and what are the different characteristics of modern AR that should be taken into account.

2.1 Dam monitoring and safety control

Dams are critical components of countries' hydric and energy infrastructure. They provide both the general population and industry, including the agricultural, with water and clean electricity. Dams can be built of concrete, masonry, earth or rock and they can be of the arch, embankment and gravity types, among others[1]. Nevertheless, these all share one common feature. They are, in general, massive structures whose malfunction or collapse can potentially disrupt the economic sustainability of a region or, worse, endanger human lives. For these reasons, dams are subject to tight monitoring and scrutiny. This is done within the scope of an activity known as "safety control of dams", which includes the monitoring and evaluation of the different components of the dam, including the dam structure, its foundation, the reservoir, and the downstream area of the dam. The safety control of dams is also performed on several domains, including structural (through SHM), hydraulic, operational and environmental [2].

2.1.1 Structural health monitoring

SHM can be defined as the "process of implementing a damage detection strategy" [3]. This process includes the observation of the structure, the measurement and registration of relevant data regarding its condition and, by analyzing that data, the characterization of the health of the structure, throughout its service life. With this information in mind, Civil and Structural Engineers can decide on the need for rehabilitation or strengthening interventions, or even the complete shutdown of the structure's operation due to no longer adequately performing the functions for which it was designed.

[1] Types of Dams (USSD), https://www.ussdams.org/dam-levee-education/overview/types-of-dams/

Because the sum of the costs of monitoring and periodic interventions is, generally, much lower than the cost associated with the reconstruction of structures [3], SHM makes sense from an economic point of view. Furthermore, critical civil infrastructures like dams, tunnels or bridges carry an extra weight in what regards the occurrence of structural-related accidents, due to the high probability of loss of human lives. For that reason, in these types of structures, SHM has a vital importance and involves the use of devices with high availability and redundancy as well as specific methodologies and highly specialized personnel.

SHM systems typically include a network of sensors, installed *in-situ*, throughout the structure. These sensors are located in relevant points, namely those where the magnitude of the measured physical phenomenon, can reach extreme values. This includes e.g. places where structural stresses and displacements tend to be theoretically higher, or areas where degradation was found in the past, through visual inspection campaigns. The values measured in the sensors are logged automatically and typically transmitted to a central structural database or, registered manually on a regular basis.

There are few other types of structures where the relevance of SHM is as big as in the case of dams. In that context, the concept of SHM is closely linked to the activity of safety control of dams.

2.1.2 Safety control of dams at LNEC

For the safety control of dams, LNEC regularly performs various activities, with the main goal of ensuring the integrity and performance of these structures, throughout its service life.

These activities include [4]:

- Data collection using monitoring equipment installed *in-situ*;
- Analysis and forecast of structural behavior, based on numeric and semi-empiric models;
- Visual inspection campaigns that allow both the detection of structural and constructive pathology and the verification of the proper functioning of the observation system itself.

The Department of Concrete Dams (DBB) at LNEC is responsible for monitoring the behavior and controlling the structural safety of 70 of the biggest concrete and masonry dams in Portugal [5]. One of these structures is the Cabril Dam, a double curvature concrete arch dam, built in 1953, which is used in this work as a case study. It is located in the Zêzere River, on the border between the counties of Pedrógão Grande and Sertã [6] and it's considered the highest arch dam in Portugal, with a height of 132 meters [7]. The top (crowning) of the structure has a length of 290 meters and the central console has a thickness that varies between 4,5 and 19 meters [6]. On the downstream base of the dam there is a hydroelectric power plant and two semi-hidden tunnel spillway outputs, one in each river bank.

The Cabril Dam includes a set of sensors and other devices, directed at the monitoring of the upstream and downstream water levels, vertical and horizontal displacements both in the structure and in the foundation, relative movements in joints and cracks, temperatures of the air, the concrete and the foundation, extensions in the concrete, foundation uplift, drained (inflow) and infiltrated flows and dynamic accelerations [6].

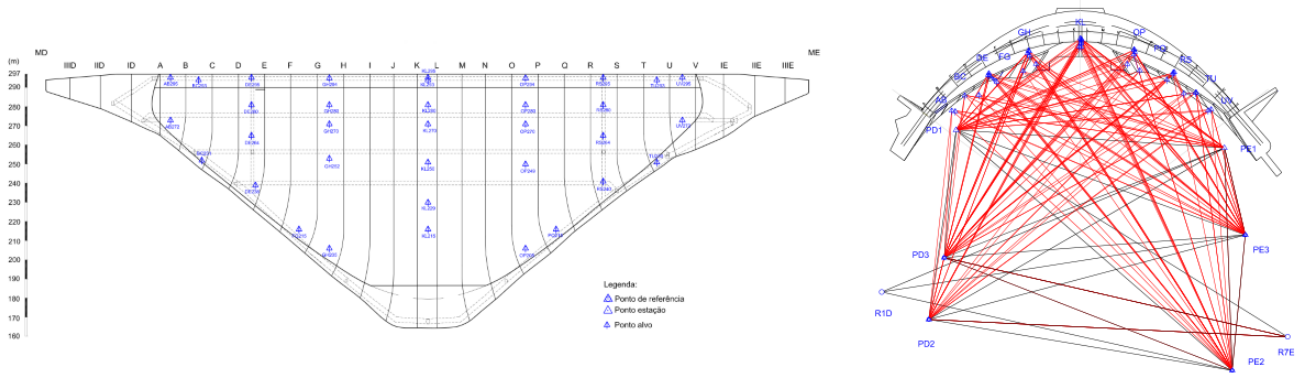


Figure 2.1: Location of geodetic marks (left) and exterior triangulation network (right) (*Image: LNEC*)

The monitoring of horizontal displacements in the structure, which is focus of this work, is carried out mainly through three processes:

- Using geodetic methods [6], namely through exterior triangulation by means of a network of fixed marks installed in the downstream face of the dam (Fig. 2.1);
- Through 10 plumblines [6] installed in vertical holes in the interior of the dam structure (Fig. 2.2);
- By means of Global Navigation Satellite Systems (GNSS) equipment, using two receivers installed, respectively, in the central point of the top of the dam and in the outskirts of the dam. This last one is used solely as a reference station [4] (Fig. 2.3).

The measurement of displacements through geodetic methods is done with portable electronic equipment of the Total Station Theodolite (TST) type, which allows the determination of the position of the fixed geodetic marks installed in the downstream face of the dam. This type of equipment is operated by a specialized technician that, from predetermined points located on the downstream of the dam, points the equipment successively to each of the marks, thereby establishing a triangulation network that enables the determination and control of the displacements.

The measurement of displacements with plumblines implies that the technician moves, along the galleries situated inside the dam, to the points where the extremities of the plumblines are located. Using devices called ”optical coordinometers” [4] [6], the technician then records the readings (Fig. 2.4(c)).

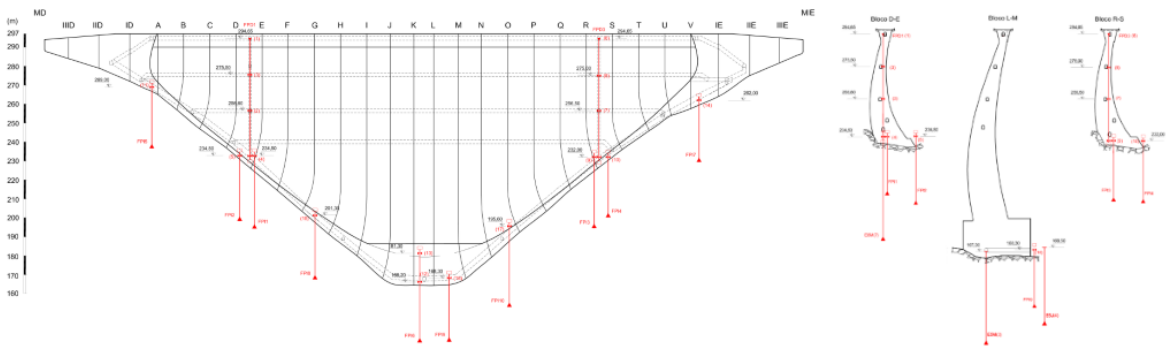


Figure 2.2: Location of plumblines in the interior of the dam (*Image: LNEC*)

Figure 2.3: Location of the GNSS receivers (left) and detail of the GNSS antenna at the top of the dam (right) [4]

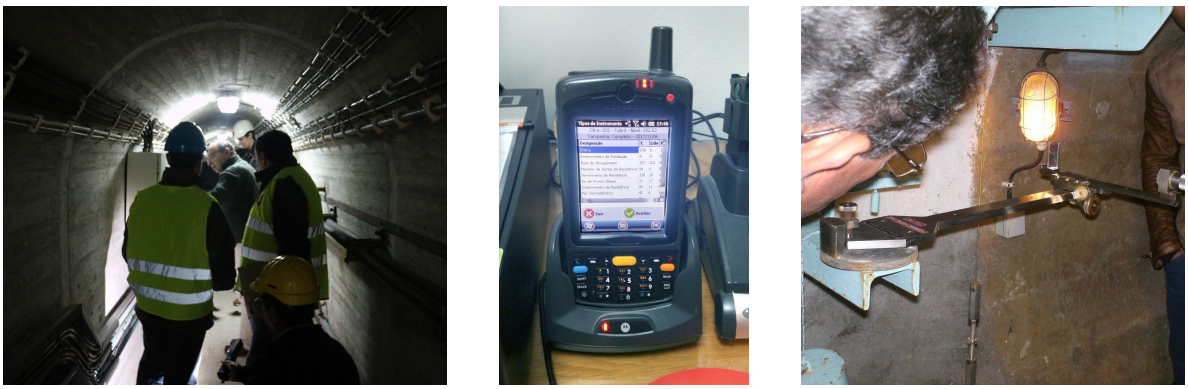
The GNSS system installed in the Cabril Dam allows continuous and automatic acquisition of positional data, enabling the monitoring of the displacements through the use of specialized software [4].

In addition, within the framework of the *Regulamento de Segurança de Barragens* (RSB) regulation and the work plans established between LNEC and the company *Energias de Portugal* (EDP) (owner of the dam), the observation system itself is inspected on an annual basis. This implies that the technicians identify and test all the devices installed in the dam and also the instruments used for measuring and logging [6].

The inspection campaigns of the Cabril Dam, carried out by LNEC, can be divided into 2 categories:

- Technical visits: Have the objective of collecting data from the sensors and other equipment. These are typically carried out by Observation Technicians.
- Formal visits: Have the objective of evaluating the safety conditions of the dam. These are typically carried out by a party of Engineers from LNEC, the dam operator (EDP) and the Portuguese Environment Agency (APA).

The technical visits require that, among other tasks, the technical staff walks along the 4 inspection



(a) Inspection party inside the galleries of the Cabril Dam

(b) PDT used by LNEC for data logging

(c) Using an optical coordinometer to read the displacement in a plumbline

Figure 2.4: Inside the galleries of the Cabril Dam during the course of inspection visits (a)(c), and equipment used for registering measured values (b). (*Images: LNEC*)

galleries (Fig. 2.4(a)) that exist inside the structure of the dam (at 293,95 m, 274,50 m, 255,50 m and 239,00 m altitudes [6]), to collect the readings from the several sensors. Data logging is done with the help of Portable Data Terminals (PDT's) (Fig. 2.4(b)). For that, the Observation Technicians need to plan in advance, using the blueprints with the location of the sensors, the best path to take through the galleries, in order to cover the desired sensors, as fast and efficiently as possible. Likewise, during the formal visits, the inspection party needs to know the location of the different sensors and equipment. It also needs, among others, to analyze the evolution of measured values, in order to assess the compliance of the structure with the safety standards.

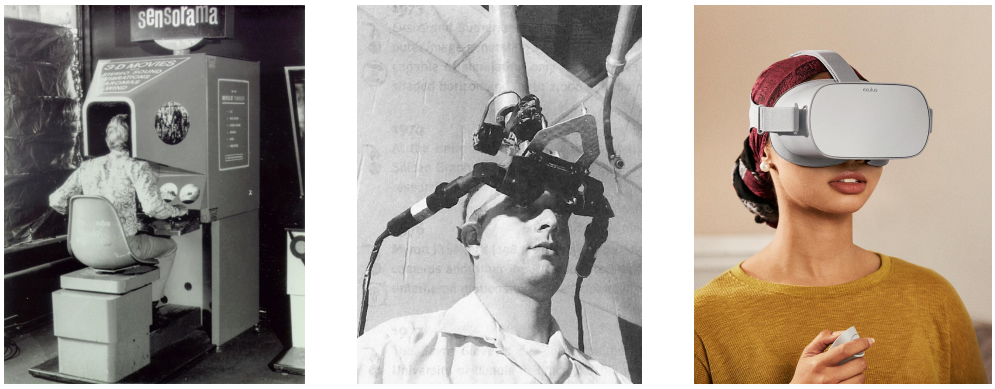
2.2 Virtual and augmented reality

The emergence and rapid evolution of new visualization technologies in the last few decades have deeply influenced the way we look at the world that surrounds us. VR and AR are two of the most widely used and most promising of those technologies, because of their capacity to immerse the user in simulated environments or enhance, in a multitude of ways, the observed reality, respectively.

Despite the concepts of VR and AR being often associated and even confused, they represent very different technologies and experiences for the user. While in VR the reality is replaced by a simulated digital world, in AR, the real world is enhanced by the superimposition of different types of information. Nevertheless, the history and evolution of these two technologies is deeply interconnected and one cannot tell the story of AR, and predict its future, without mentioning VR, and vice versa.

2.2.1 Evolution of VR

The term "Virtual Reality" was first used, with its current meaning, in 1987 by Jaron Lanier in the scope of the systems developed by his company Visual Programming Lab (VPL), namely the "EyePhone", a VR head-mounted display and the "Data Glove", an input device, worn like a glove, for mid-air human–virtual environment interaction [8]. The concept or VR, however, was born many decades before. One of the most significant milestones of its history was the invention of "Sensorama" (Fig. 2.5(a)), in the late 1950's, by Morton Heiligm. In its patent application, in 1960, Heiligm describes his device as an "apparatus to stimulate the senses of an individual to simulate an actual experience realistically" [9]. Sensorama was a booth that would allow the user to sit and fit his head inside a "hood" with a display, where a movie would be shown, with binaural sound. Special devices would use compressed air to simulate wind inside the booth as well as smells and vibrations, in accordance with the context shown in the screen. At the same time Heiligm would also obtain another patent, of the "Telesphere Mask", a device with very similar physical characteristics to those of a modern VR HMD but that was aimed solely at watching TV in a stereoscopic display [10]. In that scope, Ivan Sutherland created, in 1968, the first real VR HMD (Fig. 2.5(b)). Sutherland's device would display the output of a computer program, showing a perspective image that changed as the head of the user moved, creating the illusion that he was seeing a three-dimensional object [11].



(a) Sensorama (b) Ivan Sutherlands' HMD (c) Modern Oculus HMD

Figure 2.5: Three eras in VR history (*Images: Wikipedia, are.na, Oculus*)

Lanier's VPL set of devices, on the other hand, allowed the user to have a truly immersive experience by combining a more precise VR HMD, gesture recognition and 3D virtual objects manipulation, using the DataGloves, as well as the illusion of 3D sounds.

Throughout the 90's and early 2000's, VR technologies rapidly evolved, namely in what concerns the improvement of head and body tracking technologies, as well as the development of the ability to manipulate 3D objects in mid-air and the introduction in VR, of advanced haptic technology[2], that allow the user to feel what he is touching in the virtual environment, instead of simply grasping thin-air.

A recent landmark in VR history was the creation, in 2010, of the company Oculus (Fig. 2.5(c)), by Palmer Luckey, and the popularization of its HMD, "Rift" in the following years. This product, originally the result of a *crowdfunding*[3] campaign, combined many of the virtues that a consumer oriented VR HMD should have. It included a fairly wide field of view, low latency head tracking, low cost and compatibility with a series of games and applications. It was an immediate success, with a selling rate of 4–5 per minute on the first day it was available [12], around 10 thousand backers, and nearly 2,5 million USD raised [13]. But more than a technical and commercial achievement, the significance of Oculus lies in the fact that Rift was the trigger to the VR boom in the last few years (and, by association, AR). It was also the precursor to the race between tech giants, that suddenly saw the potential of the VR market and started working on their own HMD's.

2.2.2 Evolution of AR

The term "Augmented Reality" is attributed to Thomas P. Caudell, and David Mizell from Boeing, that used it, in the early 1990's, to refer to a technology that "allows a computer-produced diagram to be superimposed and stabilized on a specific position on a real-world object" [14]. But, as in the case of VR, the concept was born long before the term. In fact, it is widely accepted that the first VR HMD, developed in 1968 by Ivan Sutherland, and described in the previous section, was also the first AR HMD. Indeed, Sutherland's device superimposed images to a real background.

[2]Getting to Grips with Haptic Technology, https://techcrunch.com/2017/01/11/the-reality-of-vrar-growth/
[3]Crowdfunding explained, https://ec.europa.eu/growth/tools-databases/crowdfunding-guide/what-is/explained_en

(a) Videoplace (b) Using Hololens (c) Playing Pokémon Go

Figure 2.6: Three milestones in AR history (*Images: timetoast.com, VR And Fun, Bulbapedia*)

In 1974 Myron Krueger, who had been working, since the late 1960's, in a set of what he called "artificial reality" technologies, created "Videoplace" (Fig. 2.6(a)). This system/art installation, generated a responsive environment by analyzing real-time images of users, not requiring the use of any wearable hardware. Instead, it projected the silhouettes of users in a screen and, by determining its movements, would allow them to interact with other graphical objects [15].

In the 1980's and 1990's, AR systems were used to superimpose information to live TV, namely weather visualizations and virtual markers and lines during sport events. In his paper "A Survey of Augmented Reality", published in 1997, Ronald T. Azuma established the main principles of AR and the guide lines to its future, defining it as a technology that allows to "see the real world, with virtual objects superimposed upon or composited with the real world" [16]. And in 1998 NASA created the Hybrid Synthetic Vision system, that would allow the pilots in the X-38 experimental re-entry vehicle to view, overlaid to real time video of the outside, map and navigation data [8].

The open-source tracking library ARToolkit was first released in 1999, by Hirokazu Kato. It quickly became widely popular for the fast development of AR Applications. This was especially due to its effective use of computer vision[4] algorithms to determine, in real-time, the relative position of the observer and the object of augmentation [17].

In 2004 a group of researchers from the Bauhaus University developed the first AR application that could run on a consumer cell-phone. The system could detect and differentiate multiple markers and render 3D graphics into the real-time video captured by the cell-phone camera [18]. And Tomohiko Koyama created in 2009 FLARToolKit, that enabled the use of AR inside web browsers, by adding the capability of recognizing markers and calculating its orientation and position in the 3D world [18]. In 2011, Qualcomm launched QCAR/Vuforia, an AR Software Development Kit (SDK), still widely popular to this day, that allowed the detection of multiple types of targets, including real world images [19].

In early 2015, Microsoft announced the launch of Hololens (Fig. 2.6(b)), an HMD that included a self-contained computer with a dedicated holographic processor as well as wireless connectivity. The system could detect the position and motion of the user through a set of environmental sensors [20]. It included a vast collection of AR applications and became an immediate success, attracting other tech

[4]What is Computer Vision?, https://hayo.io/computer-vision/

giants to the AR market.

Between mid and late 2010's many new HMD's where announced or launched, notably "Project North Star" [21] by the company Leap Motion, that aims to create a low cost HMD with precise hands tracking, or "Meta"[5], by the company with the same name, which is primarily aimed for business users, such as product Engineers and Architects [22]. Also noteworthy is Magic Leap One[6], with a size much closer to a pair of glasses than its competitors.

A recent landmark in what concerns the adoption of AR, and also one of the most fascinating phenomena in the history of behavioral sciences in technology, was the rise (and fall) of the mobile game Pokemon GO. Launched in 2016 by Niantic, Pokemon GO was a simple treasure-hunt-like game for smartphones and tablets. It used AR technologies and the Global Positioning System (GPS) to represent in real-world locations, virtual Pokemon creatures, superimposed to reality (Fig. 2.6(c)), that the player had to "capture" and "battle" [23]. In the first 80 days after its launch, around 550 million people installed the app and, in that period, Niantic had a revenue of over 470 million USD [24]. Although the application was far from a technological achievement and the fall of Pokemon Go was as fast as its rise, its popularization showed the world the potential of AR. And, as important, it convinced the technology giants that people wanted AR, and that AR had an unsurpassable role in the present and future of visualization.

Even though the perfect consumer AR HMD/glasses are yet to be built, and VR still is slightly ahead of AR, this situation should radically change in the next few years. In fact, the market share of AR is expected to far eclipse the one of VR by 2021, with the former reaching an expected global value of 83 billion USD, in contrast to the 25 billion USD of the latter's [25].

2.2.3 Head-mounted vs handheld displays in AR

AR hardware can be divided into two main categories: wearable and non-wearable devices. Wearable devices are those that offer the most immersive experience in what concerns the augmentation of reality. These include HMD's (Fig. 2.7(a), 2.7(b)), that can be of the helmet, headset or smart-glasses type [8]. Besides the immersion, that results from the improved "shielding" of the user from the non-augmented reality and the fact that they show the content from the exact viewpoint of the user, they have the advantage of allowing the user to have a more natural interaction with the augmented environment. This is due to the fact that these devices can typically be used with the hands free, which leaves space for the use of intuitive interaction techniques like mid-air object manipulation (or alternatively, accessories like smart-gloves and other controllers).

Despite the important advantages, HMD's still have many disadvantages whose significance often depends on the environment where they are used. Even though manufacturers are making an effort to lower the costs of production, the still very high price of HMD's is one of the most deterring factors for the adoption of these type of devices by consumers. In that scope, HMD's are also very specialized equipment that have the sole objective of being used for AR interaction, and that cannot be used for

[5]Meta, https://www.metavision.com/
[6]Magic Leap, https://www.magicleap.com/

(a) Hololens HMD (b) Magic Leap One HMD (c) Tablet

Figure 2.7: Examples of AR HMD's, the bulkier Hololens (a) and the smaller Magic Leap One (b). Also an AR application running on a tablet (c) (*Images: Tech Stock Insider, Tested, Medium*)

anything else.

Apart from smart-glasses, that still don't offer an AR experience comparable to helmets or headsets, HMD's are also still heavy, bulky and a bit clumsy to use. They typically have lots of cables to connect and drag behind and they need adjustments before each AR session. Furthermore, they are not comfortable to use for long periods of time, especially for users wearing prescription glasses. The field of vision of HMD's is also still not ideal, meaning that the peripheral vision of the user is greatly affected. This can prevent the detection of obstacles and increase the probability of accidents, making it a serious hazard especially when used in dangerous workplaces. Finally, the use of AR HMD's is still prone to originate motion sickness, although typically not as severe as with VR HMD's [26].

The second big category of AR hardware is the non-wearable devices, that includes, more notably, smartphones and tablets (Fig. 2.7(c)) and also other devices that project the augmentation directly on the physical surfaces. This last type of devices will be briefly addressed in Chapter 3.

Regarding mobile non-wearable devices, namely smartphones and tablets, they share some important advantages when compared with HMD's. They are still much cheaper, lighter and convenient. They are also every-day, multipurpose devices that are not restricted to AR use. These devices typically have good autonomy and can be carried in a pocket or bag to remote locations, without the need for the user to worry about cables. Furthermore, they allow a reasonably precise interaction with virtual objects on the screen.

Smartphones have the advantage of being easier to carry and more comfortable to operate, when compared to tablets. The smaller screen also allows the user to use a single hand, leaving the other hand free for other tasks. Tablets however, offer a bigger screen real estate and therefore are more suitable for applications that require higher precision, a characteristic that is especially relevant when talking about AR in professional/workplace environments. They also typically have better battery life, which is a determining factor in graphically intensive, power hungry AR applications (as is the case of the prototype developed in the scope of this work).

The disadvantages of smartphones and tablets coincide more or less with the advantages of HMD's, namely the lack of an immersive experience and the less natural and intuitive interaction with the augmented environment.

2.2.4 Marker and markerless AR

The recognition of the surrounding environment and the relative position of the observer to the object, surface or landscape that is being augmented, is an essential part of AR technologies. This task can typically be done through two distinct techniques, each having its strengths and weaknesses.

The first technique is the most ”traditional” and involves the use of markers. These signs are usually square pieces of paper or cardboard, where a distinct black and white pattern, with fixed size, was printed. One or more markers are then attached and scattered along or near the surface of the object of augmentation, in pre-established positions. The digital version of these predefined patterns and their relative position to the object of augmentation is also contained in the AR application. This allows, using computer vision algorithms, to analyze the real-time images captured by the devices' camera, and identify the position and size of the easily detectable patterns [8]. With this information the application can then calculate the position and orientation of the observers' camera. Despite the inconvenience of using markers, this technique can be very effective in the detection and tracking in bad lighting conditions, or when the observer is at a great distance from the object of augmentation [8]. These advantages are especially relevant for outdoor AR applications.

Markerless AR is a more recent technique and, as the name says, does not require the use of markers. For this, the technique uses existent features in the surrounding physical environment with the same purpose of visual markers but using distinct algorithms. In order to achieve good tracking, it is especially relevant that the chosen features are easily recognizable, by being sufficiently unique in the framework of the surrounding environment. This technique is much more versatile and less invasive than the use of markers.

Modern AR applications typically use one of the above-mentioned techniques combined and refined with information from sensors like accelerometers, gyroscopes, magnetometers, GPS and others, to improve tracking, location and orientation [8].

Chapter 3

Related work

Due to the massive and repetitive nature of many of the construction sector activities, even small optimizations in work processes can represent very substantial savings in manpower and materials which, ultimately, lead to an increment in revenue. For this reason, the construction industry has been in the front-line in what concerns the early adoption of emerging and innovative technologies.

With regard to AR, a lot of work has been done, in the many different areas of AEC, in recent years. This chapter will categorize and briefly describe that work.

3.1 Civil Engineering, structural, urban and architectural design

Civil, structural, urban and architectural design, because of its collaborative nature and especially because it requires the designers to imagine and conceptualize the integration of the project with what exists in the field, are some of the activities, in AEC, with the most obvious potential applicability of AR technologies.

By allowing to overlap the on-site reality or even a scaled down physical model (mockup) with the new design, together with various relevant information regarding different structural and constructive aspects, AR offers a more intuitive visualization and a clearer perception, by the designer, of the volumetric, geometric, aesthetic and functional characteristics of the final (or intermediate) product.

Regarding urban design, Yabuki et al. [27] developed an AR tool to assess urban volumetry, directed at the height evaluation of buildings for landscape regulation and preservation. This solution allows for the designer to easily visualize (Fig. 3.1) how the height of a new building or building complex will compare with adjacent constructions and how will it impact the landscape. It can help public regulatory agencies to establish limits for appropriate height of buildings taking into account the surrounding urban volumetry. It also avoids the need for the construction of costly 3D models representing the topographic configuration of the site, existing structures and objects like urban furniture, by offering the means to display resizable virtual rectangular objects (prisms) in an overlapping manner with the actual landscape. To establish the level (altitude) of the base of 3D virtual objects, the solution uses data from existing Digital Terrain Models (DTM).

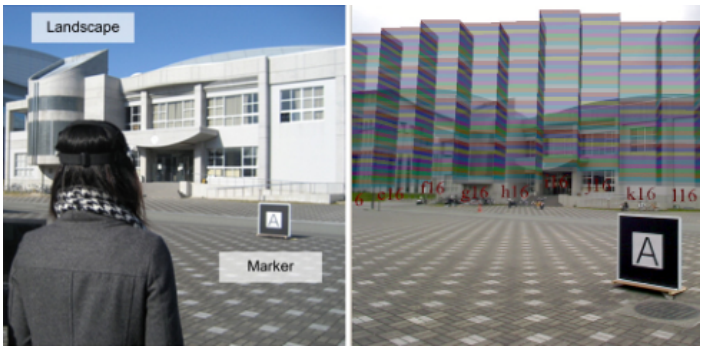


Figure 3.1: Urban volumetry computer graphics superimposed to the landscape [27]

Another fundamental aspect of the use of AR in the design activity is, due to the intrinsic multidisciplinary nature of the latter, its combination with collaborative technologies. The conjunction of these two, offers different teams of Developers, Engineers and Architects, a global perception of the evolution of the project. AR collaborative technologies can also provide an environment where team members can visually and simultaneously input their ideas and proposals to the design.

Broll et al. [28] created ARTHUR, a collaborative AR environment for architectural design and urban planning, in its different phases. The system tackles the problem created by the involvement of a large number of participants, working towards a common goal, in the design and review process of Architecture and urban projects. It provides an AR enhanced round table (Fig. 3.2) to support design and planning decisions, integrating Computer-aided Design (CAD) into the collaborative environment, without significantly altering established working processes or tools.

In what concerns structural design, Yabuki and Li [29] developed a cooperative AR solution for designing and verifying reinforcement bars layouts of structural elements of concrete bridges. The system allows for multiple users, wearing AR headsets, to concurrently move, on a surface, physical markers that represent entities of steel reinforcement bars (Fig. 3.3). The 3D virtual model of the structural steel reinforcement is overlaid to the real-world image and adjusted in real-time according to the movements and final positions of the markers determined by the designers. The solution represents a more intuitive alternative to the standard methods of conception and design of structural elements, which are traditionally characterized by its individuality and bi-dimensionality.

It is common practice, particularly in what concerns rehabilitation and requalification projects, for the

Figure 3.2: Urban designers collaborating at an augmented round table [28]

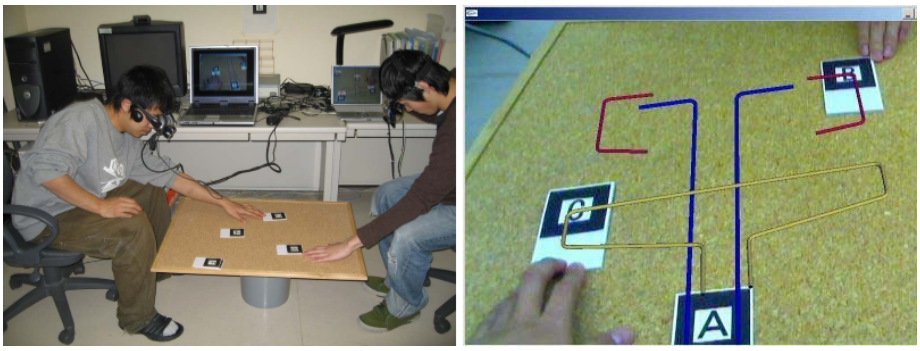


Figure 3.3: Cooperative reinforcing bar arrangement support system using AR technology [29]

designer to periodically go to the construction site in order to better imagine how elements designed in the office, look and function when integrated with the real building or structure. AR technologies offer a very important opportunity in this aspect, especially also due to the increasing movability of AR equipment.

A wearable AR system to visualize outdoor architectural features was developed by Thomas et al. [30]. This platform is aimed at the visualization of the design of buildings in the spatial context of its final physical location, allowing the real surroundings to be taken into account. It allows a user to walk around the construction site of the new building and visualize, for example, new additions to the structure, in the spatial context of the existing environment (Fig. 3.4).

The finishing stages of construction development projects can also benefit from AR technology. One example is interior design, where AR systems can allow the planner to visualize how furniture sets and object colors combine and how they affect the living space.

Pampattiwar et al. [31] applied AR technology to interior design in order to allow the designer to select, modify in real time, and then display the virtual furniture superimposed to the real environment. This application simplifies the analysis and comparison of furniture placement, making the design process more productive and precise. Likewise, Phan and Choo [32] worked on new approaches for interior design using AR technologies. Besides virtual object placement and the customization of virtual furniture in real time, the tool developed by the two researchers is additionally directed at the collaborative discussion of design choices (Fig. 3.5).

Design tasks closer to the execution stage, like the planning of construction worksites (which will be

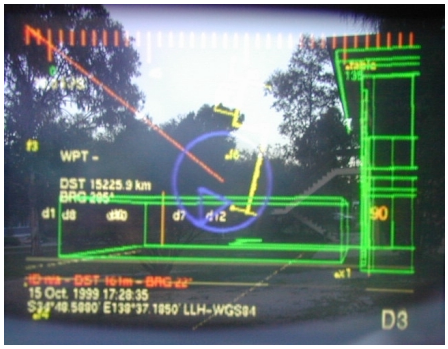


Figure 3.4: AR of the building design in the spatial context of the existing environment [30]

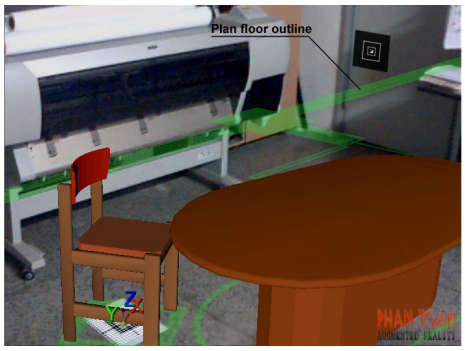


Figure 3.5: Modifying virtual furniture superimposed to the real environment [32]

addressed in more detail in the next section) can also benefit from AR, as shown by Wang [33]. This researcher developed ”AR Planner”, an AR-based construction site design tool aimed at minimizing inefficiency and preventing errors, while improving layout configuration and maximizing productivity at the worksite. The tool enables construction site coordinators and planners, wearing a HMD, to insert and move virtual 3D objects representing construction equipment, materials storage facilities or workers housing, interactively, in a virtual model, to determine the final layout of the construction worksite.

In the context of transport infrastructure, the company Arup, is integrating AR technology in its design processes (Fig. 3.6). The Civil Engineering multinational is using AR infrastructure model visualization software, together with HoloLens, to allow its Engineers to explore the design details of e.g. roads and bridges[1].

Although not directly related to design, but also worth mentioning, is the work by Marto et al. [34], which studied the application of AR to architectural and cultural heritage conservation. Their work compared different techniques and tools directed at the use of AR in exterior environments. The main objective was to identify the most suitable solutions, presently available, to be used in the future development of a smartphone AR application for viewing the virtual reconstruction of historical buildings, in the ruins of the Monographic Museum of Conimbriga. For that purpose, they elected the Vuforia SDK and the use of AR tracking with 2D images, as the ideal solutions.

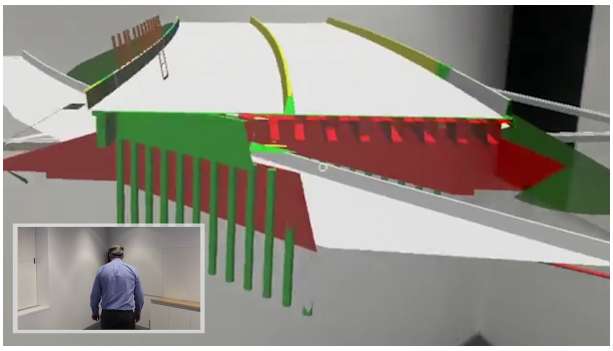


Figure 3.6: Use of AR in transport infrastructure design (*Image: Arup*)

[1]Virtual and Augmented Reality are changing the way infrastructure is designed and built, https://www.arup.com/perspectives/themes/transport/virtual-and-augmented-reality-changing-the-way-we-design-and-build-infrastructure

Figure 3.7: Cubical panorama (left) and building information model (right) [35]

3.2 BIM and construction site coordination

Besides planning and design, AR technologies can equally be useful in the execution phase of a construction project. Because this is, often, the longest stage of a project, typically consuming the most energy and the most resources, it is also the one where the use of efficient tools for the optimization of processes can lead to higher savings.

AR provides an ideal mean for accessing building information on the construction site. In that regard, it can serve as a very effective tool for extending BIM processes, taking full advantage of its 5 dimensions (primary spatial dimensions, time and cost), on-site.

Gheisari et al. [35] studied the use of augmented panoramic environments to access building information on construction sites. By superimposing building information models to augmented panoramas of sites, they found a way of providing construction professionals, a simple, natural and interactive environment to access BIM information (Fig. 3.7). Unlike a ”pure” AR experience, augmented panoramas have some static and offline characteristics, consisting of adding layers of information to a preconstructed view of the environment. According to the researchers, the use of this offline skybox virtual representation, instead of the real worldview, allows to overcome some of the limitations of a true AR experience, like the issues involving accurate registration (matching the virtual data over a physical object). This technique suffers, however, from many limitations itself, including the obvious fact that static panoramic media, representing the real world, cannot be updated in real time.

In an attempt to prevent the need for Civil Engineers to carry bulky construction drawings to con-

Figure 3.8: BIM data projected directly on building elements [36]

struction sites, Yeh et al. [36] used what they called ”projection-based AR” for on-site building information retrieval. They developed a headset, named ”iHelmet”, that integrates a projector which can display BIM data superimposed directly on building elements (Fig. 3.8). The users have to manually input their locations, using a handheld touch screen device, and the system retrieves specific building information regarding beams, columns, slabs and other constructive elements, from the building information model and projects this data on a chosen surface.

Unlike the two previous ”derivatives” of AR, Lee et al. [37] concentrated in the role of ”pure” AR to shorten the isolation gap between the building information model and reality. These researchers focused their work not solely in the use of AR technologies to present relevant BIM information superimposed to reality, but also in the contextualization of that information, to enable users to easily understand the content. By evaluating the results of personal interviews, made to a group of Architects, Civil, Structural, Mechanical and Electrical Engineers, regarding the comparison of the usefulness of different AR graphical reproduction options of BIM, they concluded, for example, that these users tend to find texturized models (Fig. 3.9) more useful than wire frame and other simpler types of 3D representations.

The company Bentley developed a prototype aimed at facilitating the on-site interpretation of 2D construction drawings [38]. Their study had the objective of overcoming the mental difficulties of matching 2D drawings with reality, by combining it with 3D models in an augmented reality context. When the user selects an element in the 2D plan, the corresponding 3D entity automatically gets highlighted in the augmented environment (Fig. 3.10). This North American software company also studied the use of HoloLens to assist workers in tasks of plant maintenance. The prototype developed by Bentley provides workers with detailed instructions regarding repair or maintenance of industrial equipment, in an AR context[2].

Park et al. [39] developed a framework for construction defect management, by integrating AR technology with BIM and ontology principles. In this framework, AR is used to detect defects in the construction site, by comparing what was foreseen in the project, via BIM data, with what was actually built. By matching BIM geometrical information with real world images, the system can detect both situations of omission/excess of constructive elements (Fig. 3.11), e.g. the installation of a wrong number water pipes and dimensional errors, like the execution of a window opening with a shorter width than expected.

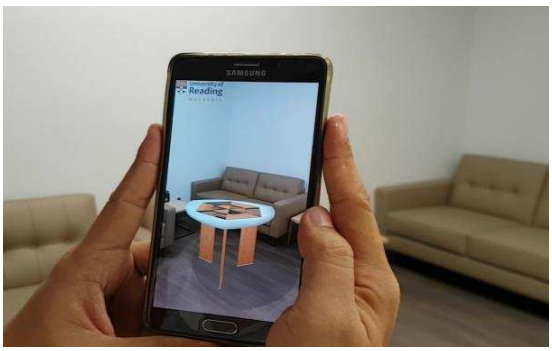


Figure 3.9: AR texturized model. [37]

[2]Using HoloLens to facilitate plant maintenance, https://communities.bentley.com/other/old_site_member_blogs/bentley_employees/b/stephanecotes_blog/posts/using-the-hololens-to-facilitate-plant-maintenance

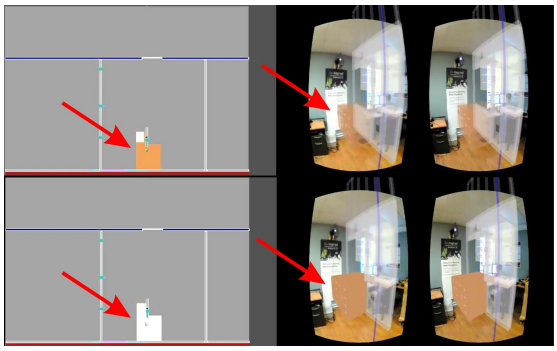


Figure 3.10: Highlighting entities in the AR environment by selecting elements in the 2D plan [38]

This allows not only for a reactive approach, by enabling site inspectors to verify the conformity of the construction with the project, but also preventive and more proactive measures, by allowing construction workers to automatically compare their work with the design, before moving to the next task.

The Swedish construction company NCC is starting to offer its clients, AR solutions that are integrated with BIM. These solutions[3], targeted for HoloLens, can merge 3D models with reality and are aimed at inspecting and visualizing progress in construction sites, assisting heating, ventilation, and air conditioning (HVAC) assembly and presenting life size models of buildings, on site, during the early stages of construction.

Berlin-based Exozet[4] solutions combine BIM, AR and VR to offer remote support to maintenance technicians on site, by connecting them with experts in specialized tasks. The on-site technicians use HoloLens and work in an AR environment, while the remote experts use a VR HMD that allows them to see what the technicians are seeing and provide precise instructions in a shared AR/VR environment (Fig. 3.12).

Elevator manufacturer ThyssenKrupp is using AR technology to improve the safety and efficiency of service Engineers, by providing on-site remote guidance[5]. The AR environment used by ThyssenKrupp

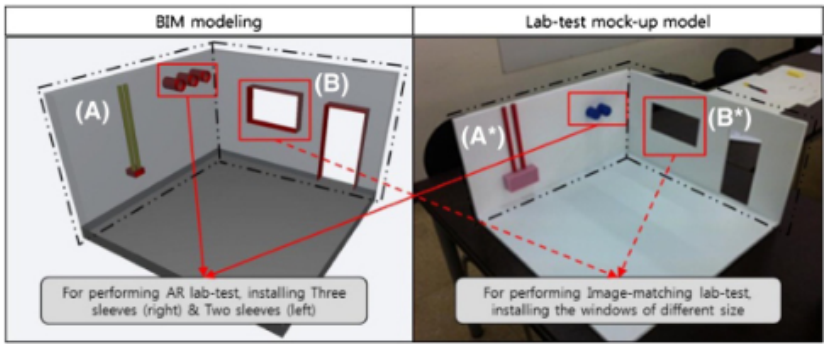


Figure 3.11: The comparison between the 3D BIM model and a mock-up model allows the detection of dimensional errors and omission/excess of constructive elements. [39]

[3]NCC HoloLens AR solutions, https://www.ncc.group/our-offer/customer-values/digital-construction/hololens/
[4]Exozet, http://www.exozet.com/
[5]Microsoft HoloLens enables ThyssenKrupp to transform the global elevator industry, https://blogs.windows.com/devices/2016/09/15/microsoft-hololens-enables-thyssenkrupp-to-transform-the-global-elevator-industry/

Figure 3.12: Using BIM and a shared VR(top)/AR(bottom) environment for remote support (*Image: Exozet*)

centers on the use of the HoloLens Skype application[6] and allows Engineers to receive instructions while keeping their hands free to perform their tasks (Fig. 3.13).

The BIM content platform, BIMobject[7], has developed an AR solution that allows its users to test and visualize on-site, superimposed to the real world, the vast catalog of BIM objects available in the platform, in a multi-person cooperative augmented environment.

As seen in the previous cases, due to the generalization of BIM processes, a fundamental task in the use of AR technologies in the construction site, is the seamless integration of BIM objects with AR. Therefore, it is important that the virtual objects used in AR systems derive from those in BIM elements, e.g. CAD files, either directly or indirectly, as concluded by Jiao et al. [40].

AR technology can also be used to aid construction equipment operators in their tasks, as shown by Chi et al. [41], that developed an AR User Interface (UI) for tele-operated crane systems. This advanced AR UI provides the operator with relevant information, superimposed to the real-time images captured by several cameras installed on the crane, to enhance operation and decision-making (Fig. 3.14). The set of information given to the crane operator includes the planned erection path, allowing for the safe

Figure 3.13: With AR, technicians can be hands free while on the job (*Image: ThyssenKrupp*)

[6]HoloLens Skype, https://www.microsoft.com/en-us/hololens/apps/skype
[7]BIMobject, https://vr.bimobject.com/

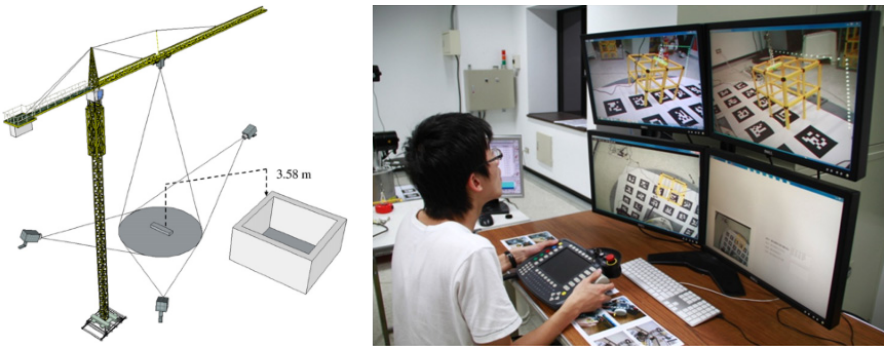


Figure 3.14: AR multi-camera crane UIs can enhance the operation and decision-making [41]

identification of securing/releasing positions and possible erection alternatives. Detailed elevation information is also displayed in the multi-screen operating station, for improved collision avoidance. Usability tests showed that the new UI promoted higher efficiency and less mental load when compared with conventional operation interfaces.

3.3 Infrastructure and building inspection

In the activities of inspecting and maintaining underground infrastructure, the use of AR technologies can be very advantageous. Unlike in other applications, AR systems can, in this case, be used not only to display relevant information regarding the infrastructure characteristics but, more importantly, can help the inspectors locate and visualize the existing infrastructure itself by superimposing its 3D model, adjusted in depth, to the image of the surface of the pavement. This type of infrastructure, due to its underground nature would, otherwise, be invisible to the inspector, that could only guess, by applying a mental transformation from blueprints or geographic information systems (GIS) to reality, the place where the subterranean cables and pipes are exactly located, and its orientation.

AR solutions for the inspection of underground infrastructure, that could provide the inspector with a kind of ”X-ray vision” to determine where underground infrastructure lies, were studied by Schall et al. [42]. These solutions provide not only a faster and more accurate way of localizing the subsurface assets, but also allow the reduction of risks of accidentally damaging the infrastructure during excavations. One of the problems, that was addressed by the researchers, was the fact that simply overlaying virtual 3D models of hidden infrastructure on top of visible real-world images does not give an appropriate sense of depth perception. In fact, virtual entities will appear like they are floating, because of overdraw. To attenuate this problem they used an ingenious trick that consists in representing a virtual hole in the ground that, through partial object occlusion and motion parallax makes it seem like e.g. the virtual water pipes and other infrastructural elements are in fact located underground (Fig. 3.15).

Also Behzadan and Kamat [43] studied the integration of AR technologies, together with GPS, to represent, superimposed to live video streams of the real world, CAD models of the underground utilities (Fig. 3.16). The solution, once again, aimed to minimize the risk of inadvertently damaging underground infrastructure during maintenance works, which may represent significant financial loss or even life-

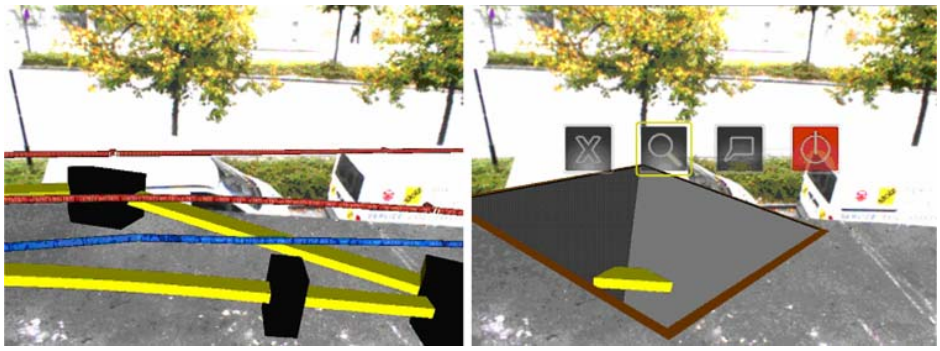


Figure 3.15: Through partial object occlusion and motion parallax the virtual infrastructural elements seem located underground (right), instead of floating in the air (left). [42]

threatening situations. They focused their work largely on finding a solution that would be as precise as possible in what concerns positioning and that could be used to guide excavation equipment to the correct locations. For that purpose, they proposed the use of techniques like Real Time Kinematics (RTK) that can improve GPS accuracy levels.

Schall et al. [44] on the other hand, developed an AR system for virtual ”redlining” (term used for manually annotating plotted or digital utility network plans) of underground infrastructure. This activity is essential for maintaining an updated scenario of what, in fact, exists in the field, bridging the gap with the planning being devised in the office. The AR redlining system can, like the previous solutions, overlap virtual 3D representations of the networks to live video of the real world (Fig. 3.17), allowing the inspector to have a clearer perception of what lies underneath the street level and produce quicker and more precise annotations. The system was designed to build its 3D augmented representations from several sources besides GIS systems, including several types of legacy data. This is done by using a Geography Markup Language as an intermediary component in the process of translating data from different sources to 3D visualizations.

In inspection tasks, AR technologies can also be successfully applied to buildings physics, like demonstrated by Liu and Seipel [45], that developed a solution for the augmented visualization of thermographic data, used in building diagnostics. This AR tool allows the superimposition of information regarding thermal infrared (TIR) surveys, to real images from building facades (Fig. 3.18), making it easier for inspectors to identify insulation deficiencies or to circumscribe structural and functional building

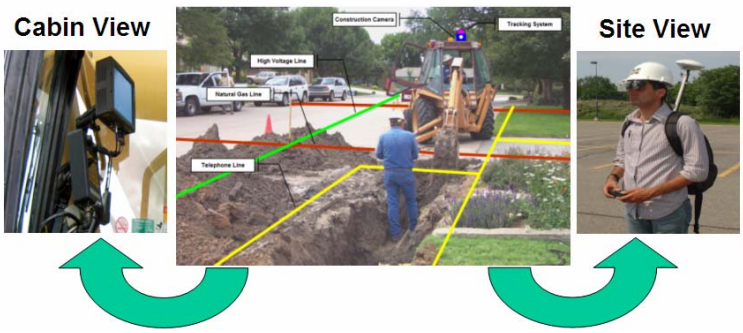


Figure 3.16: Superimposition to a live video stream, of CAD models of underground utilities [43]

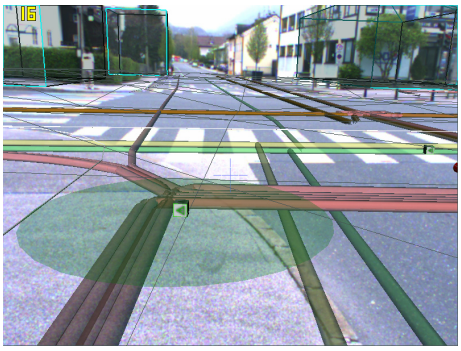


Figure 3.17: Use of AR in virtual ”redlining” of underground infrastructure. [44]

pathology. One of the main aspects addressed in this work was image registration, that allows, through the estimation of a transformation model, for sensed images to be aligned with reference images. This task was further complicated by the fact that it involved the use of different modalities of images (TIR and visible) and also by the fact that TIR images have, in general, low quality, namely low spatial resolution and lack of visual details. To hinder this problem, the researchers adopted a feature-based image registration method that uses windows, which are ubiquitous elements on building facades, in order to establish feature correspondence between images.

3.4 Structural health monitoring

The field of Structural Engineering can also benefit greatly from the use of AR technologies, especially in what concerns the inspection and monitoring of structures like bridges, tunnels or dams.

The use of more practical and intuitive solutions that allow faster and more precise information querying and gathering, regarding structural degradation or directed at the virtual representation and management, *in-situ*, of structural sensing networks, can significantly reduce the time and global costs of inspection campaigns.

Regarding SHM and more specifically, the activity of structural inspection, Peres et al. [46] developed an AR solution that allows inspectors to access information concerning the location and geometry of cracks in concrete dams. This simple solution superimposes markers, symbolizing the existence of cracks, to real time video captured with a mobile device (Fig. 3.19). When the user selects a marker, the

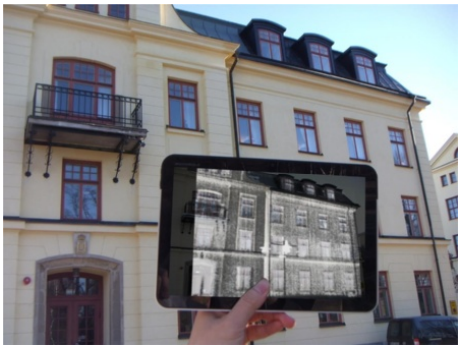


Figure 3.18: AR system for augmented visualization of thermographic information [45]

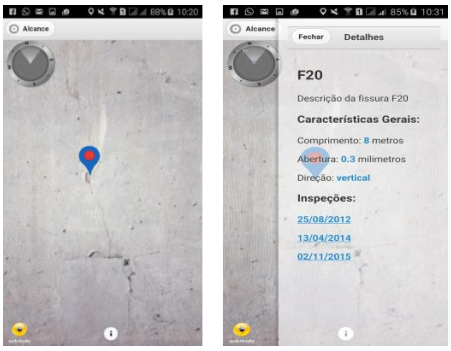


Figure 3.19: Dam cracks location (left) and crack details (right) [46]

application presents detailed information about the crack, including its length, orientation and aperture as well as dates of the previous inspections and corresponding photos. To help in the visualization and identification of areas with different levels and density of degradations, these markers have distinct colors depending on the characteristics and severity of the cracks.

Koo et al. [47] proposed ”WIVA”, a wireless sensor networks monitoring framework based on AR, directed at SHM of buildings. This AR solution allows the superimposition, to the physical structure, of a 3D model representing the real time graphical data collected from wireless structural sensor networks.

The use of AR technologies in the inspection of steel structures was analyzed by Shin and Dunston [48]. The study aimed to find out if AR systems could be used as a more practical substitute for the conventional TST or laser scanning, commonly used in the inspection of steel columns during construction. They analyzed ”ARCam”, an AR prototype system for inspection that does not require, like the traditional equipment, a time-consuming setup procedure. Instead, the system takes advantage of a tracking mechanism to get the position and orientation of the structural elements and generate the 3D virtual models that will be superimposed with the real elements and serve as comparison in the detection of constructive nonconformities. The study concluded that such AR solutions can achieve acceptable precision for confirming compliance of structural elements with standard tolerances, in inspection operations. Although the study was directed at the inspection in the construction phase, some of the principles can be extrapolated to SHM on the operational phase, namely the control of deflections in metallic structural elements.

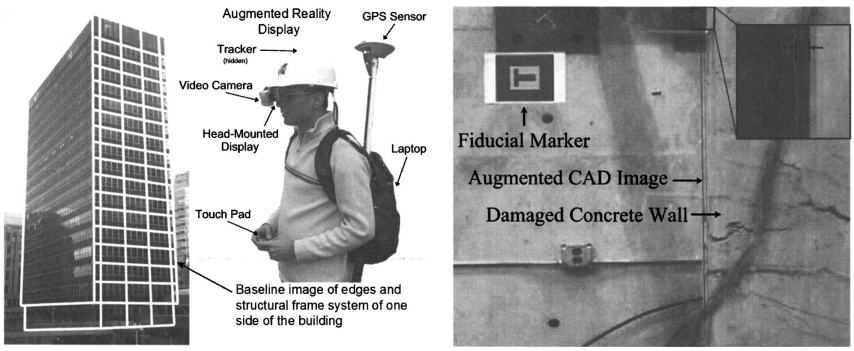


Figure 3.20: Overview of damage reconnaissance methodology (left) and displacement between registered augmented CAD image and real damaged concrete (right) [49]

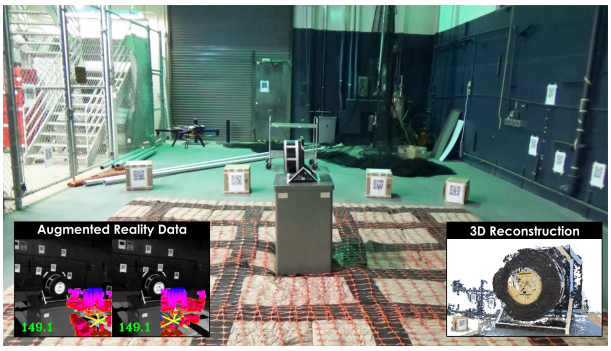


Figure 3.21: During the operation of the aerial robot, the human operator exploits the AR interface in order to create new viewpoints that better focus the inspected object [50]

The fast and accurate evaluation of damage sustained by buildings and other structures, after catastrophic events, is critical to determine the structures safety and its suitability for occupancy.

The feasibility of using AR in the assessment of earthquake-induced building damage was studied by Kamat and El-Tawil [49]. In their work, the quantification of structural damage was carried out by automatically detecting differences between the post-earthquake condition of the structures and augmented views of the structures in their original configuration (Fig. 3.20). The method assumes however that the pre-earthquake geometrical characteristics of constructions are properly documented, and adequate 3D urban models are available.

Papachristos and Alexis [50] investigated the potential to enhance structural inspection processes by combining automated aerial robots with AR interfaces. The objective of their work was to allow a remote operator, using an AR interface, to adjust the predefined trajectory of an aerial robot during a structural inspection flight (Fig. 3.21). This aimed to address the problem of inaccurate inspection and mapping of structures for which a prior model exists but is not accurate, in automated path planned aerial robotic flights. In their solution, the user ”sees” through a camera mounted on the aerial robot and, to the live video feed, the AR system overlays a real–time derived tridimensional map (built from 3D scanning) of the environment. By comparing the real structure with the model, the user can seamless adapt, ”on–the-fly”, the next robot viewpoints using head motions. Although the scope of the study was the inspection of mechanical and not Civil Engineering structures, similar ideas and principles may be applied to the latter.

3.5 Discussion

In this section, the characteristics, advantages and disadvantages of the different AR techniques and solutions presented herein, are compared and discussed.

In Table 3.1, relevant features from different solutions are compared, including the integration with existing BIM/GIS/DTM models, the need to use AR markers, the environment, interior (”Int.”) or exterior (”Ext.”), to which the technique is directed at, and the type of AR information and objects generated, as well as its collaborative nature.

Regarding the use of AR to evaluate the visual impact of a building or structure in the built environ-

AR Solution	Integration	Markerless	Environment	AR Objects	Colab
Building height [27]	DTM	-	Ext	Buildings	-
Enhanced round table [28]	CAD	-	Int	Buildings	✓
Reinforcement bars [29]	CAD	-	Ext+Int	Reinforcement	✓
Outdoor architecture [30]	CAD	✓	Ext	Architectural plan	-
Interior design [31]	-	-	Int	Furniture	-
Collab.interior design [32]	CAD	-	Int	Furniture	✓
Worksite planning [33]	CAD	-	Int	Equipment+Materials	✓
BIM panoramas [35]	BIM	✓(*)	Int	Building model	-
BIM projection [36]	BIM	✓(*)	Ext+Int	Building model	-
BIM contextualization [37]	BIM	✓	Int	Building model	-
Construction defects [39]	BIM	-	Ext+Int	Building model	-
Tele-operated cranes [41]	-	-	Ext	Erection paths	-
Infrastructure X-ray [42]	GIS	-	Ext	Infrastructure	-
Inf.maintenance [43]	CAD	✓	Ext	Infrastructure	-
Redlining [44]	GIS	✓	Ext	Infrastructure	-
TIR buildings[45]	-	✓	Ext	TIR information	-
Dam cracks [46]	-	✓	Ext	Crack markers	-
WIVA [47]	Sensors	-	Ext+Int	Structural data	-
ARCam [48]	CAD	-	Ext+Int	Steel columns	-
Structural damage [49]	-	-	Ext	Buildings	
Aerial robot [50]	-	-	Int	3D scanning data	-

Table 3.1: Comparison between solutions (* Panoramas/projection technologies)

ment, the prototype developed by Yabuki et al. [27] used DTM data to position simple 3D virtual objects representing future buildings. Although straightforward, the solution requires the placement of an AR marker in a specific pre-determined point and the selection of the computer graphics scale before visualizing the virtual buildings using an AR HMD. This solution also uses simple geometry only models, which are, according to Lee et al. [37] deprecated by AEC professionals in favor of texturized 3D models and 3D models containing 2D information.

Unlike ”passive” applications, the solution presented by Park et al. [39], takes into account the built environment and gives the user a proactive role in the detection of construction defects. Through the use of an AR interface that superimposes BIM geometrical information with real world images, the system can aid the user in inspection or construction tasks.

Similar principles but applied in the realm of structural inspection were used by Shin and Dunston [48] and Kamat and El-Tawil [49]. They both resorted to existing urban and structural elements geometrical data as the basis for the detection of alterations and evaluation of damage sustained by buildings during catastrophic events as well as the spotting and correction of constructive nonconformities.

The ”X-ray vision” principle, studied by Schall et al. [42] and Behzadan and Kamat [43] can be an incredibly useful tool for Civil and Structural Engineering applications. This concept could be, with some adaptations, transposed from the infrastructure area to structural inspection, and in this process, some of the concepts introduced by Nobuyoshi Yabuki and Zhantao Li [4], regarding the geometrical arrangement of steel reinforcement in structural elements, could be useful.

Schall et al. [42] solution also tackled the problem of virtual entities appearing to float on top of the real ones, due to the subterranean nature of the infrastructure. This aspect is not just an aesthetic detail but an important feature for appropriate sense of depth perception.

The virtual ”redlining” proposed by Schall et al. [44] addressed the aspect of doing precise annotations in engineering plans, a feature that, once again, can be easily transported to the structural

inspection domain.

A transverse characteristic to many of the solutions studied, was the use of AR markers, which can be a necessary evil in some cases and, in others, a significant hindrance in the practicality and the desirability of adoption of an AR system.

In the ”markerless” domain, the solution presented by Liu and Seipel [45], resorted to the detection of quadrilateral features on building facades to match the real-time video with static, low quality, TIR images. The ”markerless” aspect of an AR solution is a highly desirable characteristic and, combined with the direct or indirect derivation of virtual AR objects from BIM, as explained by Jiao et al. [40], can turn a system into a truly ”turnkey” solution that does not require complex or time-consuming tinkering from the user.

The tool developed by Peres et al. [46] uses simple virtual markers (not to be confused with physical AR markers) to provide inspectors with the location of cracks in concrete dams. Although the colors of the markers can give an idea of the levels and density of the degradation, the solution does not provide a direct graphical representation of the geometry and extension of the cracks. Instead, it associates, to each marker, photos of the cracks, taken in previous inspections, together with other numeric geometrical data.

Unlike most AR solutions studied, that use previously obtained data to build the virtual models, the WIVA framework analyzed by Koo et al. [47] uses real time data from wireless structural sensor networks, which is a significant step ahead from other systems. This ”on-the-fly” representation can be very valuable for other types of applications, e.g. for monitoring the behavior of Civil Engineering structures during dynamic events like seismic occurrences.

The enormous advantages of a symbiotic relationship between machine and man through AR were demonstrated by Papachristos and Alexis [50] that combined the capacity for human discernment to evaluate the most advantageous viewpoints, with autonomous inspection aerial robots, to improve the quality of 3D scanning. As with the AR UI for tele-operated crane systems, developed by Chi et al. [41], the perspective of the user is not his own, but that of a camera installed on a remote equipment or location.

As discussed in the next sections, the chosen approach took into account some of the aspects previously covered. These include the integration with existing blueprints and models [40], functionalities like ”X-ray vision” [42] and also the use of 3D models that can offer the user a better experience [37]. Also important, especially in the choice of techniques and tools directed at the use of AR in exterior environments, was the comparative study of Marto et al. [34]. On the other hand, features like the use of real time data, from wireless structural sensor networks [47], to build the virtual models, although relevant for SHM, fall outside the scope of the proposed work.

Chapter 4

Requirements

For the purpose of developing this work, it was fundamental to understand what the requirements of LNEC and the tasks associated with those requirements, were. This was done through a series of interviews with LNEC technical staff, where the way dam observation activities are carried out, was explained. These included the preparatory steps before an inspection, the means involved in the inspection itself, the different steps that inspectors take to analyze and document the structural integrity and also how office tasks are performed, after the field work is finished, among others. The operation of the ”GestBarragens” system (which is part of LNEC’s Dam Safety Information System), was equally demonstrated by an Observation Technician. A technical visit to the Cabril Dam was also made, where a multidisciplinary team (composed of two Civil/Structural Engineers and a Geographical Engineer from LNEC together with a Technician from EDP), responsible for the safety control of the dam, explained in detail and demonstrated the process of observation and structural evaluation, *in-situ* (Fig. 4.1).

It was also important to realize what kind of information LNEC found most relevant to be addressed by this work. This included defining the scope of the work, pertaining the case study mentioned above (e.g. if it would be focused on the upstream or downstream faces of the Cabril Dam or other specific portion of the structure) and outline what were the subsets of structural data that the work would be focused on (e.g. structural stresses, structural degradation or repair work characteristics and location).

Furthermore, it was crucial to identify what were LNEC expectations regarding this AR system, as meeting those expectations was a determining factor in the evaluation of the ”success” of this work. This feedback was the starting point for a user-centered design and development of the prototype, with its different components.

4.1 General requirements

LNEC proposed the development of an AR system which would facilitate the identification of the location of the different sensors and measuring devices aimed at the determination of horizontal displacements in the structure of the dam. The system would offer LNEC technical staff, the dam owner and the other entities involved in periodical inspection visits, a more intuitive perception of the distribution of

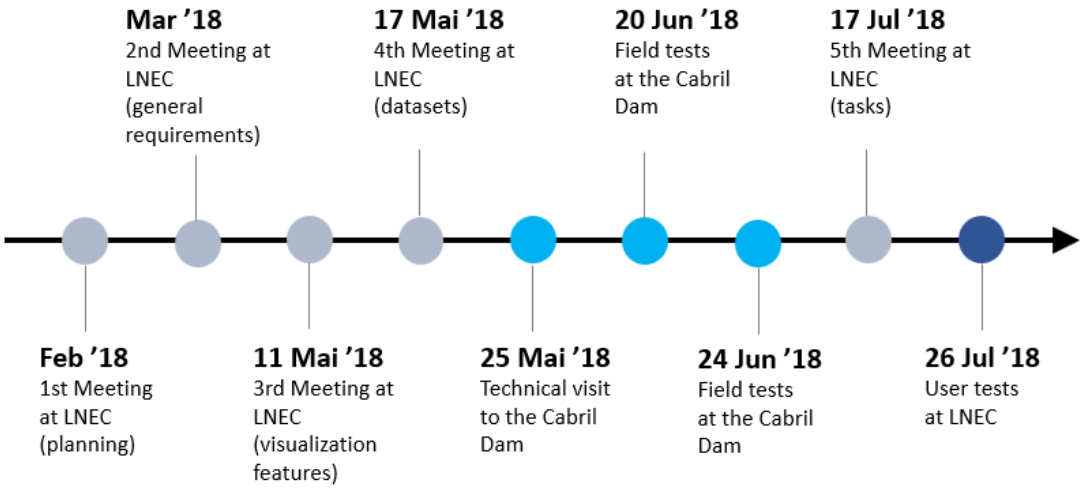


Figure 4.1: Meetings, technical visits and tests at LNEC and Cabril Dam

the monitoring devices network. Additionally, LNEC suggested the inclusion in the system, of other functionalities, namely the possibility of graphical visualization of the evolution of displacements values registered by the sensors.

The main requirements of LNEC for the AR system can, therefore, be summarized as follows:

- The ability to view *in-situ*, superimposed to the dam, the position and geometrical configuration of the different sensors and geodetic marks;

- The possibility of selecting a specific sensor and view the evolution of the displacements and other relevant values, pertaining than sensor;

The prototype should be designed to be used by the technical staff involved in the inspection and monitoring of the Cabril Dam. These include both experienced Civil Engineers that could use the application e.g. to visualize *in-situ* the evolution of dimensional/structural parameters, and Observation Technicians that could use the application e.g. to quickly locate a specific sensor in the innards of the dam during the inspection campaigns.

The users were not necessarily tech-savvy and therefore the system should have a simple and straightforward UI. They also had been using the same processes and methodologies for many years, so, a seamless integration of the technology with the established work-flow, was fundamental. That meant, for example, maintaining the existing symbolic and naming conventions.

Furthermore, it was agreed with LNEC, that the prototype should be directed at the observation of the dam from a downstream position. This position allows for the observer to have the most favorable view of the location of the network of sensors. The observation of the dam from the inside of the galleries, using AR, will be left for future work.

4.2 Data

The operation of the monitoring systems and the inspection campaigns generate very high volumes of data. This data is stored electronically in LNEC servers and is accessible to the technical staff through the GestBarragens system. The data includes numeric logs from accelerometers installed along the structure of the dam, concrete thermometers, strain gauges, electrical "Carlson" strain meters, elongometer's bases, flow meters and foundation piezometers. It is also comprised of images, maps, engineering blueprints and models.

LNEC pointed out the horizontal displacements' values, and its evolution with the air temperature and upstream water level as the most relevant data for the scope of this work. It was agreed that the system should be focused on the visualization of horizontal displacements data obtained through 3 types of sensors/devices: geodetic marks, plumblines and GNSS.

For that purpose, the following datasets, originated from GestBarragens, were made available by LNEC:

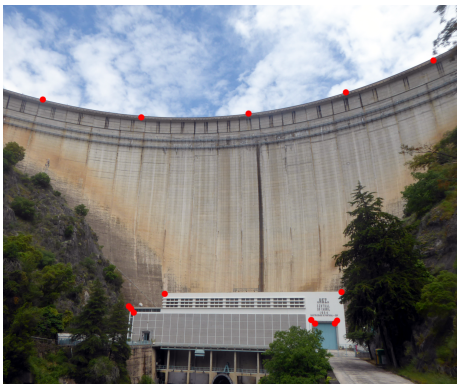
- Displacements measured in Plumblines: Containing the evolution of tangential and radial, relative and absolute, displacements between 1954-2018, as well as the measurement date (approx. 14 000 entries/lines);
- Displacements measured in GNSS: Containing the evolution of the x, y, z coordinates of the position of the GNSS station located in the central point of the top of the dam, between 2016-2018, as well as the measurement date (approx. 400 entries/lines);
- Water levels: Containing the evolution of the upstream and downstream water levels, between 1954-2018, as well as the measurement date (approx. 115 000 entries/lines);
- Temperatures (1954-2014): Containing the evolution of the maximum and minimum air temperatures between 1954 and 2014, as well as the measurement date (approx. 13 000 entries/lines);
- Temperatures (2014-2018): Containing the evolution of the average air temperatures between 2014 and 2018, as well as the measurement date (approx. 30 000 entries/lines);

Furthermore, because GestBarragens does not include information regarding the evolution of displacements measured in the geodetic marks, LNEC provided an extra dataset containing the relative displacements measured between 1981 and 2017, as well as the measurement date.

Although in future work, a complete integration between the AR system and LNEC databases can be developed, for the purpose of this work, it was decided to use local files containing the relevant data. In that scope LNEC provided Comma-separated Values (CSV) files exported directly from GestBarragens. These raw data files are transferred to the AR device, together with the application and are automatically loaded and parsed when the AR application is initialized.

Another aspect of this process was the collection and processing of the data needed for the construction of the 3D model to be shown in the augmented environment. LNEC initially provided 2D blueprints with the location (length and width) of the sensors, to be used in the initial phase of the development,

(a) Using a TST to obtain precise space coordinates



(b) Notable points at the power plant and leveling points at the top of the dam

Figure 4.2: Determination of the sensor network and notable point space coordinates using a TST, at Cabril Dam (*Images: LNEC*)

where a photo of the dam was to be used, instead of the actual structure. These maps allowed the representation, in a vertical plane, of the sensor network model. In later stages LNEC organized a visit to the Cabril Dam, where the missing third dimensions of the sensors locations were determined using a TST (Fig. 4.2(a)), allowing the construction of a model with full 3D coordinates, to be superimposed to the real dam. This visit was also an opportunity to determine the location in space of some notable points of the Cabril Dam power plant, which was used for AR tracking purposes, and a set of leveling points located at the top of the dam (Fig. 4.2(b)), used for controlling the alignment of the model with reality.

4.3 Use case

The Unified Modeling Language (UML) Use Case Diagram represented in Fig. 4.3 has the purpose of exemplifying use cases for the AR prototype, in the scope of the safety control of dams. The system involves both Engineers from LNEC, EDP and APA as well as Observation Technicians from LNEC, EDP and multiple subcontracted Civil Engineering consulting firms (e.g. Afaplan). It serves as a visualization tool for the data contained in LNEC databases, namely, as previously mentioned, GestBarragens. It allows Engineers and Technicians to view the position of the different sensors, including plumblines, GNSS and geodetic marks. The actors can then select a specific sensor and visualize the charts pertaining the evolution of the registered displacements in that sensor, as well as the corresponding air temperatures and upstream water levels. This set of requirements had to be taken into account in the chosen approach. For that, the development of the prototype sought to implement the above-mentioned features in a way that would ensure an efficient operation in the field.

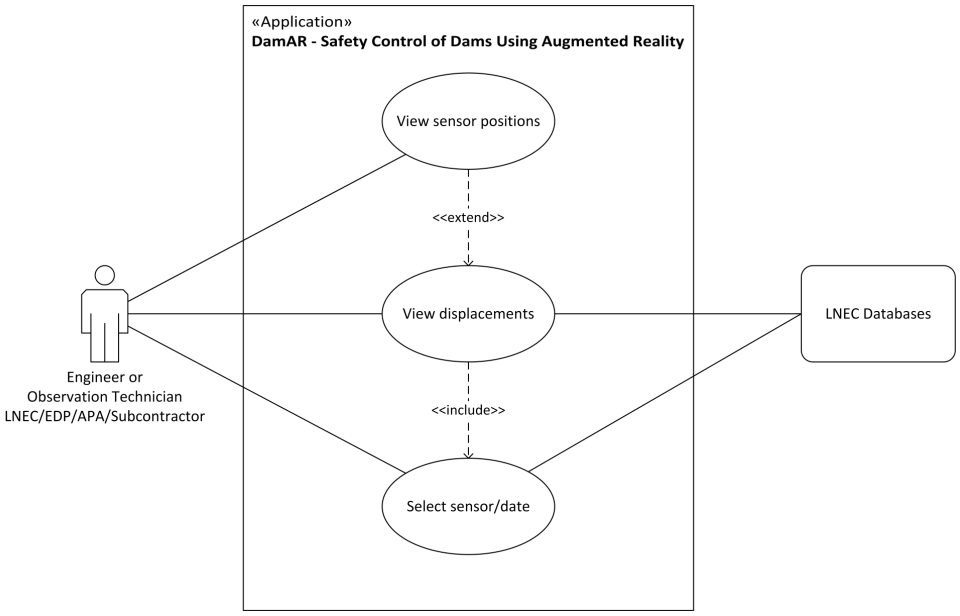


Figure 4.3: UML Use Case Diagram

Chapter 5

DamAR prototype

Based on the requirements, a prototype of the AR system was built. This prototype was developed with the objective of understanding if AR technologies could effectively be used in relevant tasks related to the safety control of dams. The prototype was named ”DamAR” and its design and development were heavily based on user feedback and field testing.

5.1 Architecture

This work is part of a wider project that aims to demonstrate the applicability of new computational tools, to the 3D visualization of information concerning large Civil Engineering structures, in order to improve work processes at LNEC. These work processes include, among others, visual inspection campaigns aimed at the collection of critical information regarding structural integrity and safety. In that sense, the prototype was designed and developed with its future integration, within the existing LNEC Dam Safety Information System, in mind (Fig. 5.1).

LNEC uses GestBarragens, a specialized information system, that allows the management of data concerning dam monitoring systems, anomalies information resulting from periodic inspections, docu-

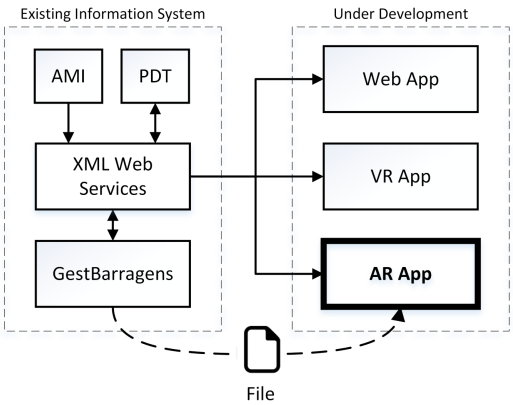


Figure 5.1: Simplified overview of the existing LNEC Dam Safety Information System and its possible future integration with the visualization apps. Also depicted (dashed link) the adopted simplified approach to retrieve sensor data, using local files provided by LNEC.

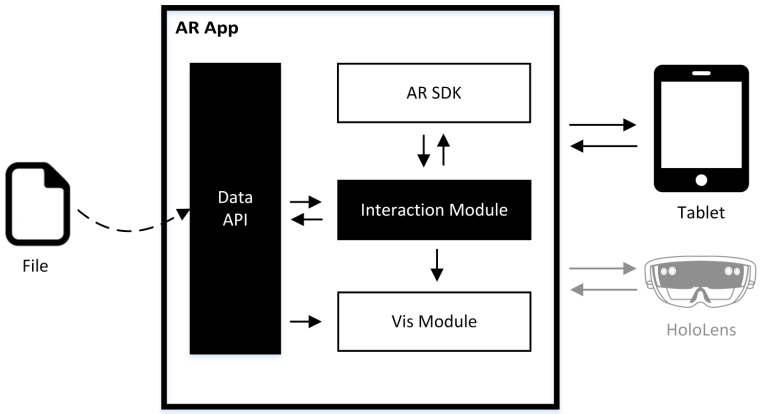


Figure 5.2: System Architecture

ments like reports, photos, diagrams, drawings concerning dams, geo-referenced information for graphical visualization and mathematical and physical models [51]. This information system has the ability to interact, through XML Web Services [52], with different types of applications. These include e.g. receiving field sensor data using Automatic Monitoring Instruments (AMI) or to obtain, *in-situ* using PDT's, data regarding the instrumentation system of a specific dam [51].

Within the above referred project, the data managed by GestBarragens, will be accessible and visualizable both through a Web App, in LNEC offices, using a VR App, or *in-situ*, using the AR App discussed in this work.

The ultimate goal is that the AR App can directly connect and use information from LNEC Databases as a basis to automatically build the 3D virtual objects that are superimposed to the real world, in the AR environment. Nevertheless, given the proof-of-concept nature or the present work, it was decided to leave this integration for future-work and adopt a simplified approach, by using data files directly exported from GestBarragens, containing sensor information. This decision was also related to the fact that most of the data necessary to build the 3D models used in the AR environment and some of the relevant sensor data (regarding displacements measured in geodetic marks) are not presently available in GestBarragens. Furthermore, given the critical and classified aspect of the data contained in this Dam Safety Information System, it would be necessary to obtain special permissions from LNEC to access it and create additional security mechanisms, related to access control, to ensure the integrity of the data during prototype testing.

The AR App consists of four main components that work together to transform the structural monitoring data into useful augmented visualizations, as depicted in Figure 5.2.

The first component is the Data API, which allows the AR App to load and parse the data from the CSV format files provided by LNEC (and in future work connect and interact with the remote resources via XML Web Services). The information flows via the Data API, to a second component, the Interaction Module. This component serves as a bridge between the structural monitoring information, and the other two remaining components: the AR SDK and the 3D graphical engine (Vis Module).

The AR SDK is responsible for providing object recognition and tracking to the system. The Vis Module, on the other hand, is used to render 3D models in the AR scene and produce the final visualizations.

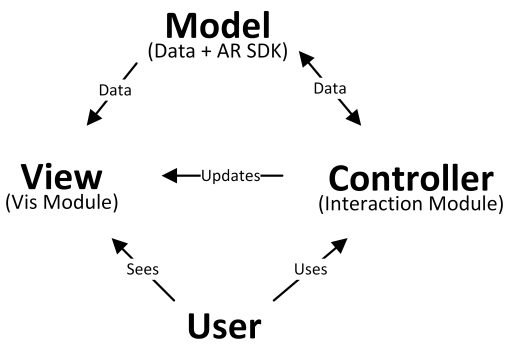


Figure 5.3: Model–view–controller representation of the system

These components follow the software architectural model ”Model–view–controller” (MVC), illustrated in Figure 5.3, where the ”View” is represented by the Vis Module, the ”Controller” is represented by the Interaction Module and the ”Model” corresponds to both the AR SDK and the data translated by the Data API. The user interacts with the system via the ”Controller” and can observe the result of its interaction in the ”View”.

Due to the popularity, practicability and low-cost of tablets, the new AR App was developed primarily for this type of equipment, but with the option of being used with dedicated AR hardware, namely Microsoft HoloLens. The latest generation HoloLens equipment can provide a satisfactory markerless AR experience. This type of wearable hardware is, nonetheless, in its current configuration, not very comfortable for users, especially if used in long inspection campaigns. It is also expensive, when compared to a common tablet, and continues to suffer from limited field of view, although some progress is being made in this aspect[1].

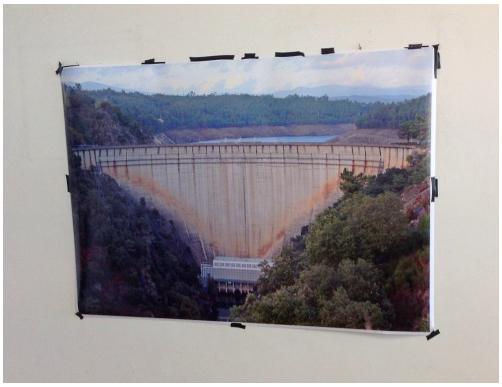
5.2 Challenges

One of the most important challenges in the design and development of the prototype was, undoubtedly, the uncertainty, which lasted until the first field tests, regarding its operation and viability in real situations. The reason for this was related to the technical challenge, both at the hardware and software level, that AR in vast spaces, namely with long-distance tracking, poses. This uncertainty meant that from the very beginning, development alternatives, directed at the proof of concept, were planned. These included the use of a reduced-scale model of the Cabril Dam that exists in LNEC or a large-format photo of the dam (Fig. 5.4). Although the latter alternative was used in some stages of development, the first field tests with the prototype revealed its suitability for use in real structures.

Another relevant challenge was related to the geometrical characteristics of the Cabril Dam itself. Concrete dams are, by nature, massive monolithic structures, with regular monochrome surfaces. This superficial homogeneity is even more pronounced when we talk about the downstream face. Although some dams possess distinctive features, namely dam spillway outputs or accessory structures on the

[1] Doubling the Field of View on HoloLens, https://hololens.reality.news/news/microsoft-has-figured-out-double-field-view-hololens-0180659/

(a) Model of the Cabril Dam at LNEC (*Image: Alfredo Ferreira*)



(b) Large-format photo of the Cabril Dam

Figure 5.4: Alternatives to the real dam considered for the development of the prototype

top, that is not the case of the Cabril Dam. Indeed, its downstream face does not have any distinctive features that can be used for markerless tracking (Fig. 5.5). To that extent, one can therefore consider the Cabril dam type, as the most unfavorable case in what concerns distinctive features susceptible of being used for tracking. For that reason, alternatives had to be found for the purpose of AR tracking, namely the use of features of the facade of the power plant at the base of the dam. Although not ideal, particularly because of its long distance from the dam structure itself, the power plant had a few distinctive features that allowed the markerless tracking to take place.

Another important challenge was the need to compile data from a multiplicity of sources, in order to build the 3D model of the sensor network. The positions of the different types of sensors were estimated from several blueprints, containing the altitude of sensors, from theoretical models of the dam and from a technical visit to the site. During this visit, TST type equipment was used to determine the exact positions of some sensors and notable points of both the structure and the power plant. These conditions led, as described in the following sections, to the need for later *in-situ* verification and calibration, so that the 3D model was as accurate as possible.

(a) Downstream face of the Cabril Dam

(b) Castelo de Bode Dam

(c) Salamonde Dam

Figure 5.5: Lack of distinctive features for AR tracking in the downstream face of the Cabril Dam (a), when compared with other Portuguese Dams (b) and (c) which possess visible spillway outputs (*Images: DroneXtreme.HD, Mapio.net*)

5.3 Implementation

The prototype was implemented in two distinct versions. The preliminary version was developed mainly with the objective of moving forward in building the UI, even before the first field visit to the Cabril Dam took place. For that purpose, a photo of the dam was used, instead of the real structure. The second version was designed to be tested and used in the field. Although these two versions share the UI, they differ in what regards the digital models used and in the way the tracking is handled, as explained in the following sections.

5.3.1 Technologies

Before the implementation itself took place, the technologies to use in the development of the prototype had to be selected. This included both the graphical engine, the AR SDK and the programming language. The choice of graphical engine fell on the widely used Unity, because of its overall performance and compatibility. In this choice it was of particular relevance the fact that Unity allows the development of applications in a desktop environment, and its direct export to a multiplicity of hardware platforms, including Android and IOS tablets and also Microsoft Hololens AR headsets.

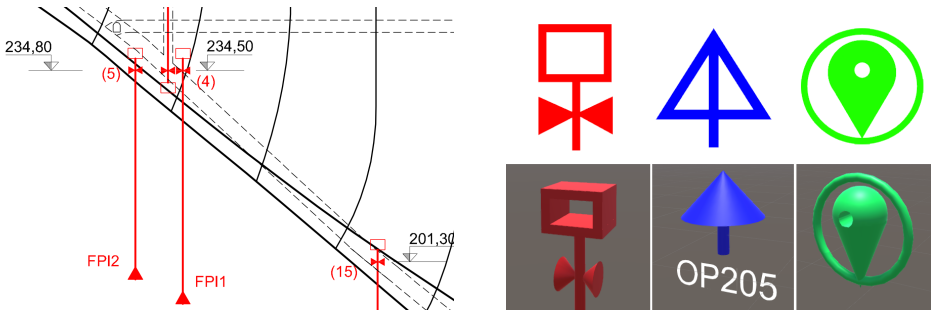
Regarding the programming language, C# (”C Sharp”) was chosen. This was simply due to the familiarity of the Author of this work, with it and the fact that C# is fairly well documented in what concerns its integration with Unity.

In what concerns the AR SDK, Vuforia was chosen. This was, on the one hand, due to its native integration with Unity and, on the other, because of its good performance in exterior environments, as concluded by Marto et al. [34].

The suitability of the Unity + Vuforia ”stack”, for the purposes of this work, was verified through the development of small test examples. These examples were aimed at testing both the long-distance tracking capabilities, in particular, its precision and stability, and the integration of Unity and Vuforia in what concerns the ability to select and manipulate objects in an AR environment.

5.3.2 Digital models and symbology

The first step of the development itself was the construction of the digital 3D models that would represent the network of sensors in the AR environment. For that it was fundamental, first, to choose appropriate symbology for the different elements of the sensor network. Although the creation and use of symbols of sensors directly based on its physical characteristics, was considered in the beginning, this option was soon abandoned. It was concluded, after some reflection, that it would likely lead to the users not recognizing the symbols, due to lack of familiarity. In fact, the symbology should be familiar to the users and allow the easy perception of the meaning and objective of each of the elements, in the scope of the different tasks related to dam observation. In that sense, after some exchange of ideas with LNEC, the choice of symbols fell on the one used on blueprints of the Cabril Dam sensor network Fig. 5.6(a), provided by LNEC via a Technical Note [6]. This symbology is the one typically used by LNEC in visual



(a) Detail of the symbology (plumblines) in a blueprint used by LNEC

(b) Adopted symbology. From left to right: plumbline, geodetic mark and GNSS equipment. On top the 2D symbols and on the bottom, its 3D counterparts

Figure 5.6: Symbology design

inspection reports and other technical documents.

Although the symbols for plumblines and geodetic marks were present in the Technical Note, there was no GNSS symbol represented. This symbol was therefore created from scratch and was inspired in a GPS map marker.

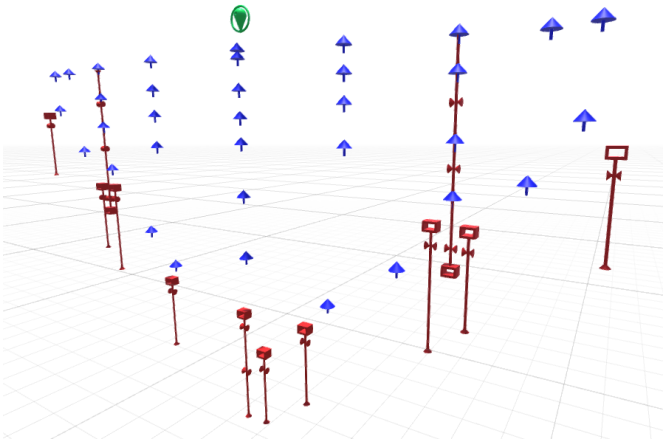
Because the model of the network of sensors would contain 3D elements, it was also necessary to create the 3D versions of the chosen 2D symbols. The adopted 2D symbology and its 3D counterparts are represented in Fig. 5.6(b).

As explained previously, two different digital models of the network of sensors were developed, using the Unity model design environment. The first one was employed in the preliminary version of the prototype that targeted a large-format printed photo of the dam instead of the real structure and the second was used for the field version of the prototype, directed at the use with the real dam.

In that sense, in the preliminary 3D model of the network, the sensors and other devices were positioned along a common vertical plane (Fig. 5.7(a) and 5.7(b)) . This plane would coincide, in the AR environment, with the plane of the photo, which would allow for the sensors to appear distributed along its surface (Fig. 5.8(a)), with different ”(X,Y)” coordinates and a common ”Z” coordinate.

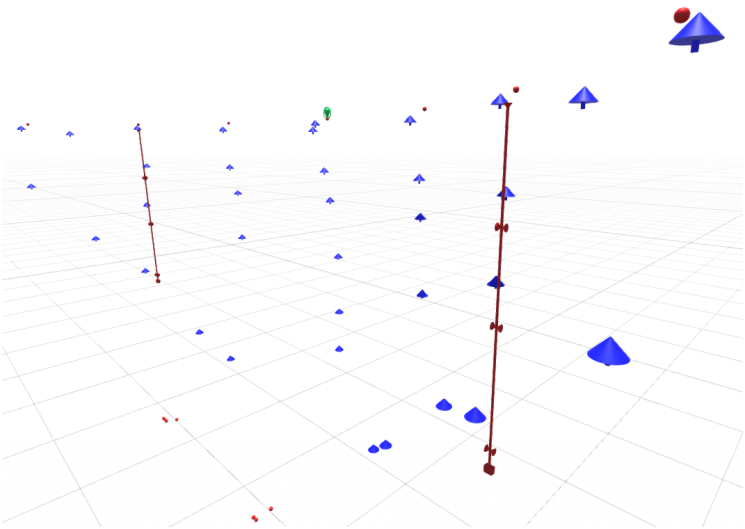
The option for the preliminary use of a photo and a ”plane” digital model was also related to the fact that, at the time of the beginning of development, the exact positions of some of the elements of the network, were unknown. For this reason, the preliminary network model was built crudely, based on the above-mentioned blueprints containing only the altitude of the sensors and the relative positions of some of the elements of the network.

In the final 3D model of the network, directed at field-use, the sensors and devices were positioned in their ”real” relative position in space (Fig. 5.7(c) and 5.7(d)). This would allow for the different elements of the sensor network to appear distributed along the downstream face and the interior of the real dam, with different ”(X,Y,Z)” coordinates (Fig. 5.8(b)).

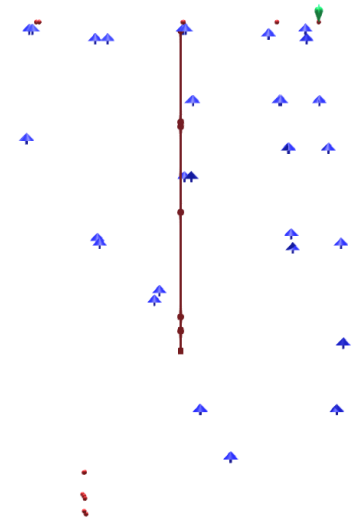


(a) General view of the preliminary model

(b) Side view of the preliminary model



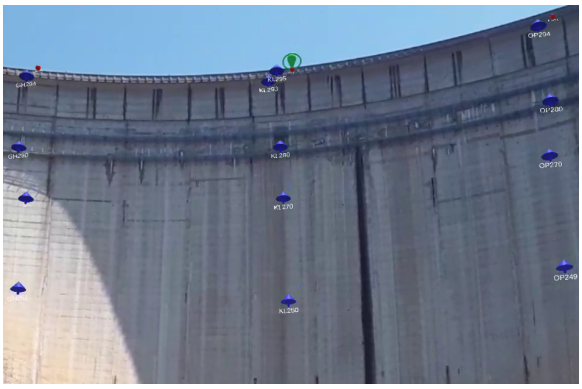
(c) General view of the field model



(d) Side view of the field model

Figure 5.7: Comparison between the preliminary (plane) model (a)(b) and the field (spatial) model (c)(d)

(a) Preliminary model of the network superimposed to a picture of the Cabril Dam



(b) Field model of the network superimposed to the real Cabril Dam

Figure 5.8: Comparison between digital models being used in an AR environment

Figure 5.9: General view of the UI.

5.3.3 User interface

The UI allows for the structural inspectors to visualize, superimposed to the real structure, different types of information relevant to its tasks. Because the system will be used on a non-daily basis and by users that may not be tech-savvy, the UI was designed to be easy to learn, simple and straightforward (Fig. 5.9).

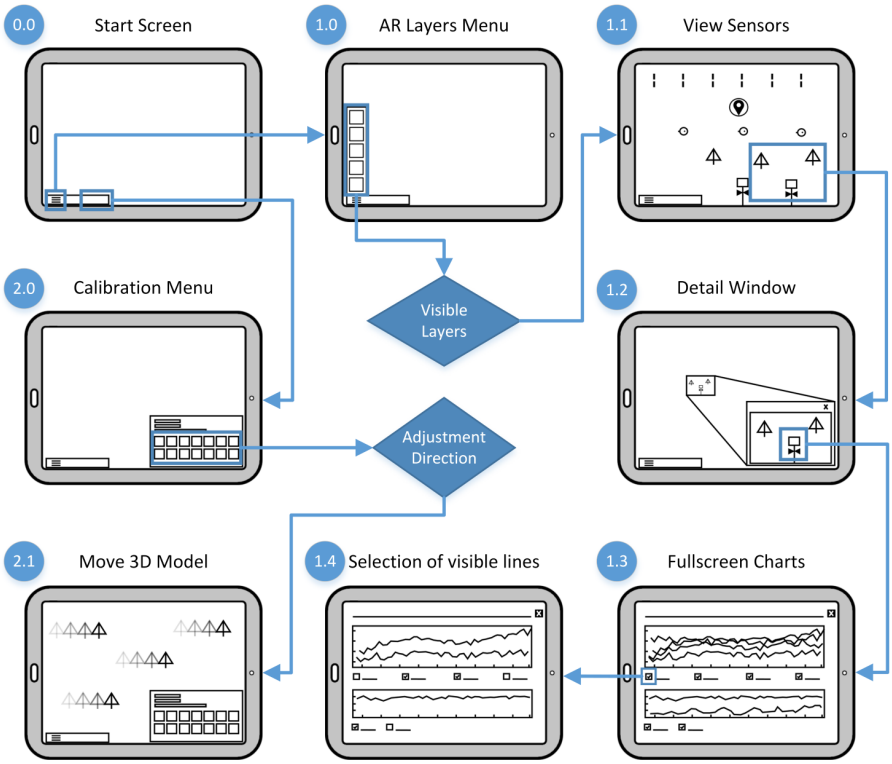


Figure 5.10: UI flow diagram.

The hardware platform for the testing of the prototype was an Android tablet and therefore the interaction of the user with the system is done using touch.

The UI includes a of a set of toolbars and menus that allow for the user to easily navigate through the different AR visualization options and horizontal displacements information. The UI flow is shown in

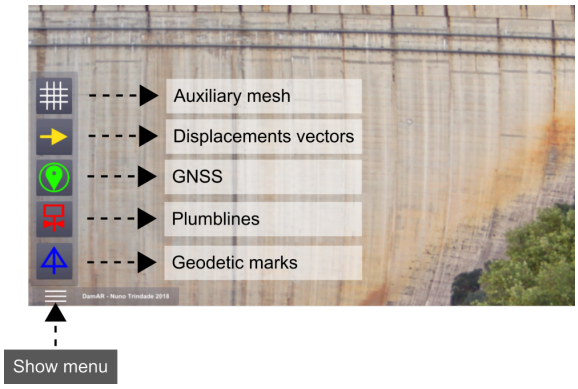


Figure 5.11: Menu that allows the user to select which visual elements should be shown in the AR environment.

Fig. 5.10 and will be explained in detail below.

In the start screen the user is presented with a small toolbar situated in the bottom-left corner. If the user taps the menu symbol situated in the leftmost area of the toolbar, the AR Layers Menu is shown (Fig. 5.11). This menu allows for the user to control which visual elements will be shown in the AR environment and is composed of 5 buttons. By selecting these buttons, the user can show or hide the different layers.

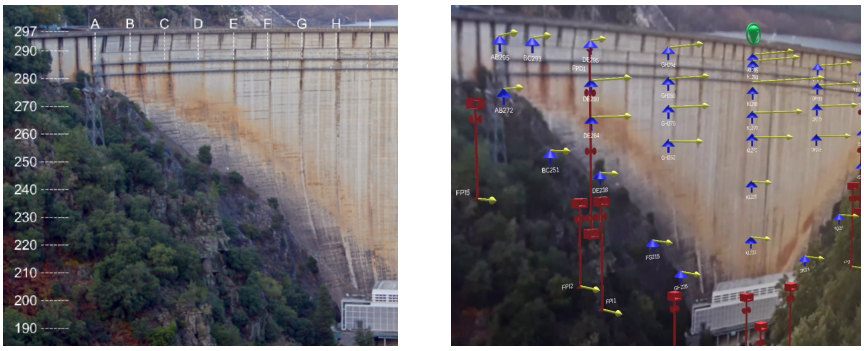
The first 3 buttons (from bottom to top) correspond to the main sensors for measuring horizontal displacements: geodetic marks, plumblines and the GNSS antenna (Fig. 5.12). The top button, allows for an auxiliary mesh to be shown, that represents the location and designation of the constructive joints of the Cabril Dam and a vertical altitude scale (Fig. 5.13(a)). LNEC staff typically uses the nomenclature of these joints when referring to a specific area of the downstream face.

Additionally, the AR Layers Menu includes a displacement vectors button directed at the visualization of displacement vectors superimposed to the dam (Fig. 5.13(b)). This option is for demonstration purposes only and uses fictitious values. It also lacks the proper controls to be useful, having been created with the sole objective of showing the appearance of a possible future feature where the magnitudes of displacements are visualized directly in the AR environment.

Depending on the layers selected, the AR environment is populated with a set of sensors and devices

(a) Geodetic marks (b) Plumblines (c) GNSS

Figure 5.12: The 3 types of horizontal displacements sensors/devices that can be represented in the AR environment



(a) Auxiliary mesh

(b) Displacement vectors represented together with the sensor network

Figure 5.13: Additional AR visualization layers

that can be selected in order to obtain further information regarding a specific sensor.

The process of selecting sensors has some implications in what concerns the comfort of using the system. When selecting a sensor that is not within ”thumb-distance” the user should typically have to hold the tablet with only one hand and tap the screen with the index finger of the other. Stabilizing the tablet with a single hand, especially in the case of tablets with thin bezels, can be uncomfortable. Also, because the system is to be used in the field and ”on the move” it’s not practical to support the tablet on a surface. In that sense, the AR environment has an important interaction advantage that can be used for the purpose of improving the comfort of use. It allows, instead of the previous selection procedure, for the user to move the tablet field of view in the direction of the sensors location in the AR environment, bringing the sensor in reach of the thumb (Fig. 5.14). This allows for the tablet to be stabilized with both hands at all times when using the AR environment.

Also in the scope of selection, an important obstacle was presented during the development, related to the precision with which the user could select the sensors. When the sensors are situated too close to each other in the sensor network or the observer is positioned too far away from the dam, the selection of a specific sensor is very difficult (Fig. 5.15). In fact, in certain conditions, the sensors appear almost superimposed, making the individual selection virtually impossible.

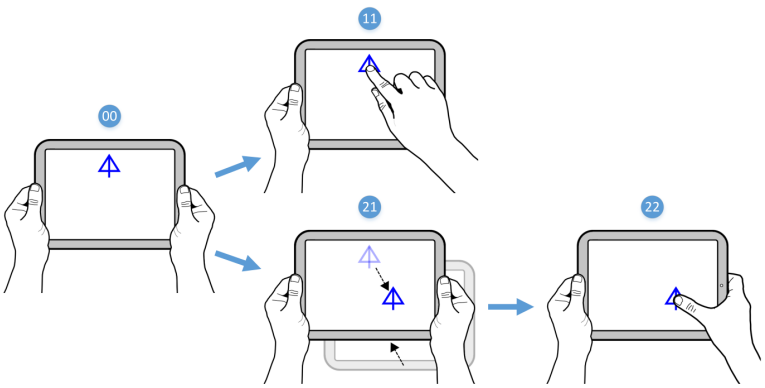


Figure 5.14: Comparison between approaches when selecting a sensor not accessible at ”thumb-distance”. Top (00-11): Using the common approach. Bottom (00-22): Taking advantage of the AR environment.

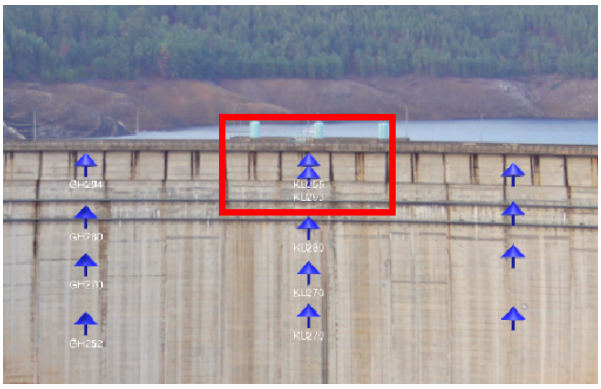


Figure 5.15: When sensors are situated too close to each other or the observer is positioned far away from the dam, the selection of a specific sensor is difficult

A way had to be found that would allow the precise selection of individual sensors, even in very ”crowded” areas. The adopted solution consisted of implementing an intermediate step in the selection process. This intermediate step consists of a detail window that shows a zoomed view of a specific region of the network of sensors (Fig. 5.16). So, instead of worrying in selecting a particular sensor in the network, the user just needs to tap in the region surrounding the location of the desired sensor. The detail window then appears, by default in the bottom-right corner of the screen, where the sensor can be selected with precision.

Furthermore, the selected area is highlighted, in the network itself, by a rectangular contour. The contour is attached to the detail window by two guide lines. These guide lines follow the movement of the tablet and allow, at all times, to establish a visual connection between the selected area and the detail window. This behavior persists, even when the selected region leaves the field of view, which allows the user to always know the location of the region that is being analyzed (Fig. 5.17(a)).

The implementation of this functionality, although apparently trivial, had a significant level of technical difficulty, because it involved the direct connection between two functional layers inside the Unity ecosystem. These layers, commonly known by ”UI” and ”World”, have significant different behavior and modes of operation and typically function in a complementary but independent way. Also, the Unity UI layer has many restrictions in what concerns the representation of certain types of objects. As a conse-

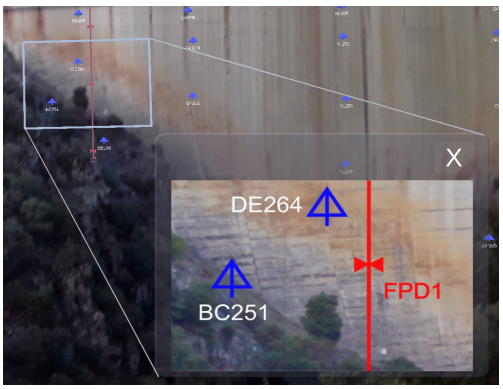
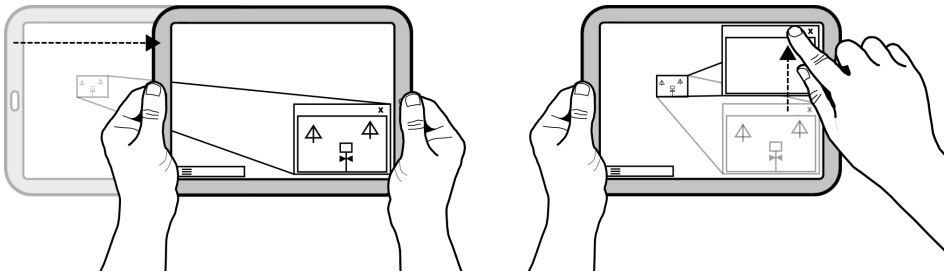


Figure 5.16: Detail window.



(a) The guide lines remain active even when the selected area is not in the field of view.

(b) The detail window position can be changed using a tap and drag movement.

Figure 5.17: Features of the detail window.

quence, some initial problems of poor performance, which were manifested by the lag and trailing effect of the guide lines, had to be overcome, before a fluid behavior was achieved.

Although the default position of the zoom window is the right-bottom corner, the window can be dragged to a more convenient position if the user so wishes (Fig. 5.17(b)). The chosen position is then maintained throughout the session, unless the user wishes to modify it.

After the user selects the sensor on which he wants information about, a fullscreen window is displayed. This shows the type and designation of the sensor and two line charts (Fig. 5.18). The top chart contains the evolution of horizontal displacement values recorded over time in that sensor. The bottom chart shows the values of atmospheric temperatures and upstream water levels measured over time in the dam. Bellow each chart there is a set of check boxes, one for each line shown in the charts, that allow the user to hide/show specific lines, further filtering the analysis.

In the particular case of the straight plumblines (FPD), because these devices include multiple positions of measurement, the top chart shows multiple lines, one for each point where values are recorded. For other types of sensors, a single line, regarding the measured horizontal displacements, in shown.

The charts are also interactive and allow the user to pan and zoom using, respectively, ”pinch” 5.19(a)) and ”tap and drag” 5.20(b)) movements, in order to display a specific region. As the user pans and zooms the labels of the vertical axis of the charts will adapt dynamically to the upper and lower limits

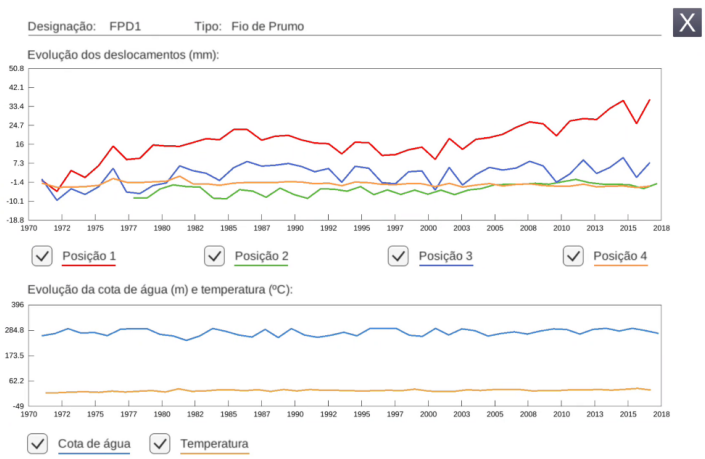
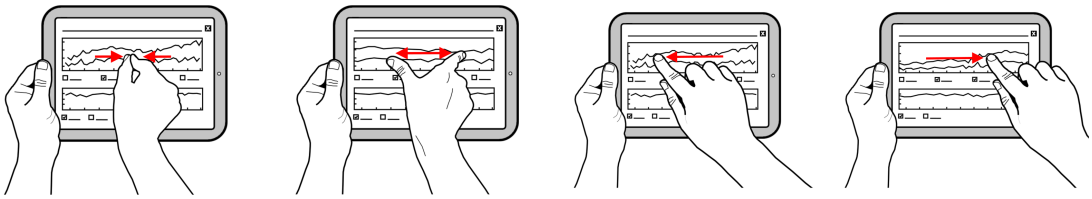


Figure 5.18: Full screen charts representing horizontal displacements, air temperatures and upstream water levels are shown when a specific sensor is selected.



(a) Pinch to zoom in-out. (b) Tap and drag to pan left and right.

Figure 5.19: Changing the views of the charts.

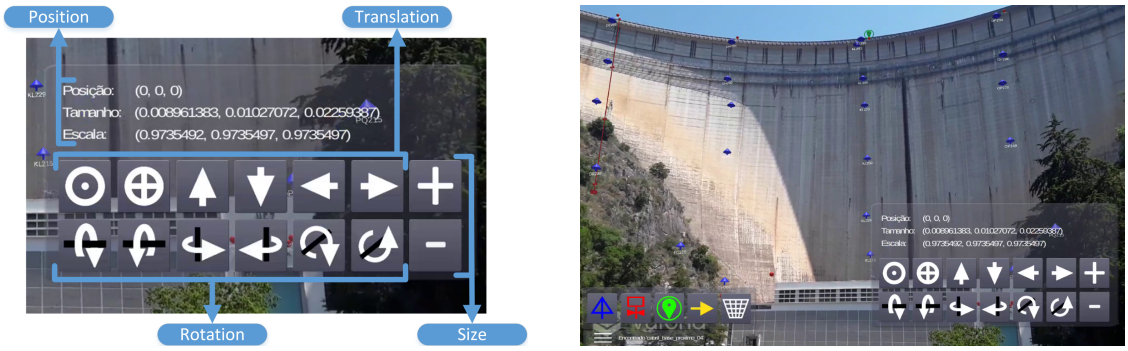
of the visible points. Also, the level on detail (year/month/day) of the date labels in the horizontal axes will increase as the user zooms. Furthermore, the view in both (top and bottom) charts is automatically synchronized. So when the user changes, through zooming or panning, the view on one of the charts, the other is adjusted to be as similar as possible, in what concerns the period of time covered. This allows for the user to easily establish a parallel between the various quantities shown (e.g. analyze the relations between the horizontal displacements and the upstream water levels in specific periods of time).

Although, due to the restricted time for development, the use of pre-made charting solutions was considered and analyzed (namely "Graph And Chart"[2], "Smart Chart"[3] and "ProChart"[4]), these did not met the specific requirements in what concerns both visualization features and integration in the UI. Due to these limitations, it was decided that the charting functionality had to be developed from scratch. Because the Unity UI System has severe limitations in what concerns the drawing of lines and other primitives, the "UILineRenderer" extension[5] was used to draw, at runtime, the chart area.

To handle the graphical representation of the large amounts of data available, in a agile manner, the values to represent in the multiple levels of zoom were pre-calculated and pre-filtered. This allowed a significant improvement in the performance of the zoom and pan operations.

The first tests with the prototype in the Cabril Dam revealed some misalignment between the digital model and reality, for reasons that will be discussed in the following sections. To ensure that the model could be aligned *in-situ*, a special Calibration Menu was developed. The menu is accessible by double-tapping the right portion of the start screen toolbar, where the name of the application is situated. It appears in the bottom-right corner of the screen and includes a set of buttons that allow for fine adjustments to the digital model's position in space, including its translation and rotation along the six-degrees of freedom (meaning the translation is possible in 3 directions and the rotation is possible around 3 axes), as well as the adjustment of the size of the sensors (Fig. 5.20). In the top portion of the menu, the current position, size and scale of the model are displayed.

[2]Graph And Chart, https://assetstore.unity.com/packages/tools/gui/graph-and-chart-78488
[3]Smart Chart, https://assetstore.unity.com/packages/tools/gui/smart-chart-103218
[4]ProChart, https://assetstore.unity.com/packages/tools/gui/prochart-46203
[5]UILineRenderer, https://bitbucket.org/UnityUIExtensions/unity-ui-extensions/wiki/Controls/UILineRenderer



(a) Features of the Calibration Menu.

(b) Using the Calibration Menu *in-situ*.

Figure 5.20: Calibration Menu for fine adjustments to the digital model's position in space.

5.3.4 Detection and tracking

As previously mentioned, Vuforia was the AR SDK chosen for the development of the prototype. Vuforia provides many different tracking techniques that differ in the type of target used. Those include the use of Model Targets, Image Targets, Multi Targets, Cylinder Targets, Object Targets and *VuMarks*[6].

Given the geometric characteristics of dams, the use of Image Targets was considered the most appropriate. This technique uses pre-captured photos of the environment to recognize it. By automatically identifying key features of those photos in the image that is being visualized in the camera of the device being used (e.g. tablet), the Vuforia engine can estimate the approximate position and orientation of the camera relative to the target. With this information, Vuforia can then represent the digital model, superimposed to reality, in the correct position.

Although, according to Marto et al. [34], the use of Image Targets does not offer the best performance, in what concerns the stability of the digital model's position, when compared to other techniques, it is less sensible to changes in luminosity, making it more appropriate for exterior environments.

Regardless of its performance, Vuforia has, however, one important disadvantage. This AR engine does not allow the creation of Image Targets at runtime. If present, this feature would allow the maximum versatility of the system by using targets that reflect the current conditions found in the field (namely regarding luminosity and shadows), and thus potentially optimizing the tracking performance. Instead, the source images have to be pre-uploaded to the Vuforia website. After processing, it is possible to download a database file containing the Image Targets. This database can then be imported to Unity/Vuforia and used in the AR application.

As explained previously, the surface of the downstream face of the Cabril Dam lacks distinctive features that can be used for tracking. The choice for building Image Targets therefore fell in the facade of the power plant located at the base of the dam. In what regards the preliminary version of the prototype, because of the static nature of the environment where it would be used, both in what concerns geometrical and luminosity characteristics, a single Image Target was needed. When that Image Target is occluded or is out of the field of view of the camera, Vuforia uses a technique known as "Extended

[6]Vuforia Engine - Attach digital content to specific objects, https://www.vuforia.com/features.html

Figure 5.21: The two architectural features chosen and examples of multiple Image Targets with different levels of luminosity and shadow coverage, to improve detection and tracking

Tracking"[7], to sustain tracking. This technique uses the characteristics of the surrounding environment and allows, depending on how detailed and feature rich the environment is, to maintain a stable tracking.

For the field version of the prototype, due to the variable environment where it is used and the large distance from the observer to the structure, to increase the probability of detection and the stability of tracking, multiple Image Targets were used. Based on both Vuforia recommendations for optimizing target detection and tracking stability[8] and the tests carried-out *in-situ*, two distinct architectural features of the facade of the power plant, were selected. These features are located in opposite positions of the facade, near the left and right limits of the building. This allows to increase the area where at least one Image target is inside the field of view, consequently minimizing the need for the use of Extended Tracking. For each of the architectural features, several Image Targets were created, each based on photos taken throughout the day, during field visits. These source pictures were selected based on its distinct characteristics in what concerns the levels of luminosity and the shadow coverage (Fig. 5.21). Although ideal, it would not be feasible, with the tools and time available for this project, to cover all

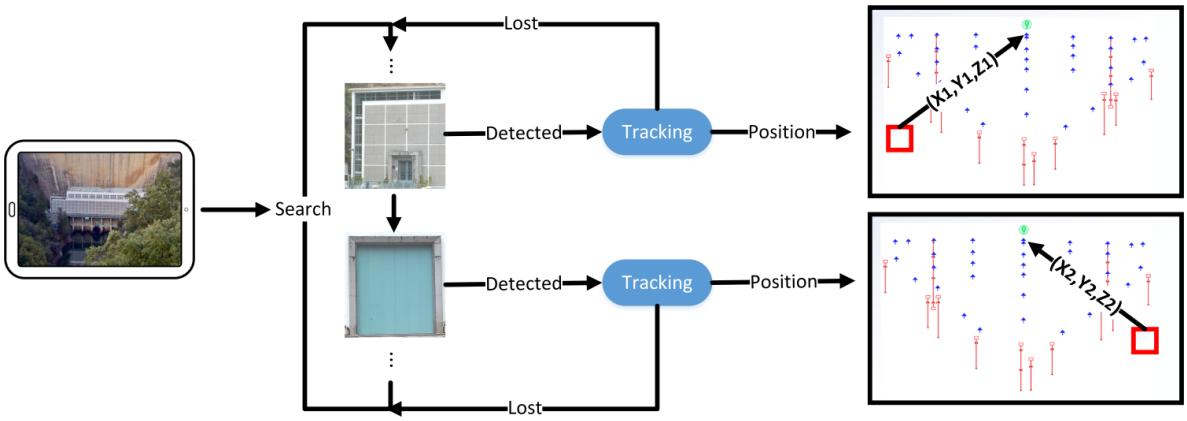


Figure 5.22: The system cycles through the Image Targets and tries to find a match. When found, the digital model is shown in the configuration corresponding to its relative position to the detected Image Target.

[7]Extended Tracking, https://library.vuforia.com/articles/Training/Extended-Tracking

[8]Optimizing Target Detection and Tracking Stability, https://library.vuforia.com/articles/Solution/Optimizing-Target-Detection-and-Tracking-Stability.html

possible atmospheric conditions and solar orientations.

When in operation the system searches, in the real time video, for the existence of any of the Image Targets (Fig. 5.22). If one is detected, then the digital model is shown in the configuration corresponding to its relative position to that specific Image Target. If the tracking is lost, then the searching resumes, as the system tries to find an Image Target that better corresponds to the present conditions (it may be found in a different feature or in the same feature but with more approximate luminosity and shadow characteristics).

5.3.5 Operation

The UI, digital models and tracking features were integrated together to obtain a functional application. The application was compiled in Unity and transferred to an Android tablet. Also transferred were the data files, exported from GestBarragens.

When started, from the Android home screen, the application first loads the structural information, air temperatures and upstream water levels, from the external data files. It then performs all the necessary pre-calculations needed to represent the different graphical features, namely the distinct views of the data charts. This phase is needed, so when in operation the user does not have to wait for the data to be processed, which would interfere in the fluidity of the UI. After this, and as the user points the tablet to the dam, the application starts analyzing the real-time video from the devices' camera and tries to detect one of the multiple targets present in the Image Target database. When it finds a target, it initiates tracking, showing the digital model in the appropriate position, superimposed to the dam structure. During this detection and tracking phase, the user can select, via the AR Layers Menu, the visual elements that are shown in the AR environment. The user can then proceed to select the desired sensors and examine its characteristics, namely the evolution of measured values, via the full-screen charts. When in this full-screen window, the user no longer needs to worry in pointing the tablet to the dam and can freely zoom, pan and compare values in the charts.

The prototype was used to validate the proposed approach, during the evaluation phase, which is addressed in the next section.

Chapter 6

Evaluation

For the evaluation of DamAR, different aspects of the prototype were taken into account. Field testing was carried out with the objective of evaluating the general performance, *in-situ*, of the prototype, including its detection and tracking capabilities. Furthermore, real-user evaluation was performed, for assessing the usability of the UI and its suitability for tasks related to the safety control of dams.

6.1 Field Testing

During the development of the prototype, three field visits were carried out to the Cabril Dam. The first one had the objective of evaluating the conditions of the environment, gathering elements to build the final digital model and capture photos that would serve as source for Image Targets. On the other hand, the remaining two visits served for field testing of the prototype. This included the evaluation of the detection and tracking capabilities of Vuforia with the selected Image Targets and, in that scope the success of the strategy of using multiple targets in multiple positions for a single digital model.

The prototype target detection capability was tested, in different points sequentially closer to the dam, along the access route that connects the National Road 2 (EN2) to the base of the dam. The successful detection of an Image Target occurred at a distance between 200 and 110 meters from the facade of the power plant. Furthermore, fairly stable tracking is achievable at around 110 meters from the facade of the power plant, (about 150 meters from the downstream face of the dam), with a distance between the observer and the tracked Image Target (corresponding to the L-shaped feature), of approximately 130 meters (Fig. 6.1). Also, at 110 meters or less, with the tablet stationary, pointed directly at the target on the left of the facade, the initial detection had a success rate of 100% (20-30 tries during the visits), even when the lighting conditions were not optimal. The detection was also achieved almost immediately (in a 1 second or less) after the application had started, was operational and the tablet was pointed at the target.

Nevertheless, it was also observed that, although detection can be achieved, the stability of the tracking is very sensitive to luminosity variations and especially to the appearance of shadows. When the existing conditions in the areas of the facade of the power plant corresponding to the Image Targets,

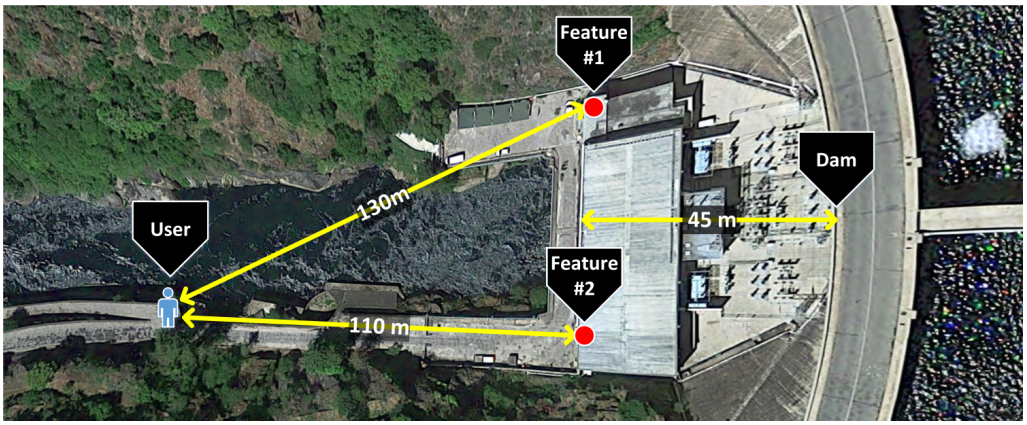


Figure 6.1: Fairly stable tracking is achievable when the user is at about 110 meters from the facade of the power plant (which is situated at around 45 meters from the downstream face of the dam), with a distance between the observer and the tracked Image Target (Feature #1), of approximately 130 meters.

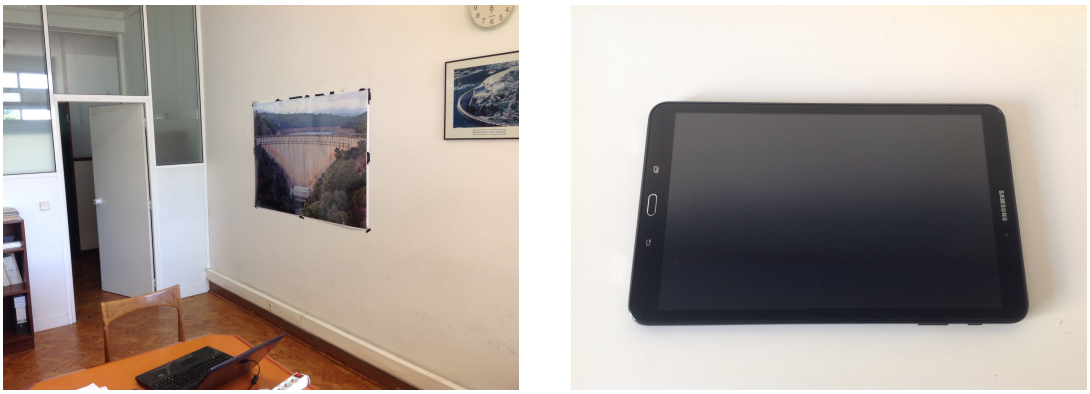
were similar to the ones on the source images, the digital model had residual oscillation. But when those conditions changed, namely, when the sun shined, and shadows covered the facade, the oscillation increased significantly, and the model moved and jumped from the initial position. In the absence of targets inside the field of view, namely when the tablet was pointed at the upper limits of the dam structure, Vuforias' Extended Tracking functionality (see Section 5.3.4) took charge and allowed for the tracking to be maintained. However, a slight increase in the oscillation of the model, was noticed.

In what respects the use of multiple targets for a single digital model, the prototype would successfully adopt, for a specific area, the Image Target whose features were closer to the existing ones (e.g. an Image Target based on a darker source image when the sun was covered or a brighter one, when the sun was shining). The transition between the use of Image Targets located on different areas of the power plant facade (when e.g. the field of view included solely the left or right portions of the facade) was also almost unnoticeable, in regard to the change of the relative position of the digital model in relation with the detected target.

The precision of the positioning of the model in the augmented environment, namely its correspondence with reality was also tested. While the superimposition of the auxiliary digital notable points (obtained through triangulation with a TST, mentioned in Section 4.2) to the facade of the power plant, was just about perfect, the network of sensors was slightly misaligned with the structure of the dam. This misalignment was especially noticeable in the top of the structure, where the digital leveling points did not coincide with reality. This problem was addressed through the introduction of calibration features.

6.2 User Evaluation

The usability of the UI and its suitability for tasks related to the safety control of dams was assessed through real-user evaluation.



(a) Test environment (b) Tablet (10.1") used to run the AR app

Figure 6.2: Test setup at LNEC

6.2.1 Evaluation methodology

The evaluation process had, as main objective, determining the usability of the AR prototype's UI, namely its suitability for field dam safety control tasks. It was also aimed at assessing if current AR technologies could, in fact, be efficiently used in relevant tasks related to SHM.

The evaluation consisted of real-user tests, using LNEC staff directly involved in the several tasks of dam observation and structural health monitoring, namely Observation Technicians and Structural/Civil Engineers, that provided first-person feedback to the system operation. This highly specialized personnel offered knowledgeable and grounded advice that was used not only to evaluate the performance of the system, but also served as a gauge for the need of improvement of existing features or introduction of new ones.

Because it was not practical to transport a large number of users to the Cabril Dam site, the tests were carried out in a meeting room of the DBB of LNEC, using, as a substitute for the real structure, a large format photo of the dam (Fig. 6.2).

The tests (Fig. 6.3) were conducted individually by each user and the tasks were performed sequentially, in a random order. The author of this work served simultaneously as test coordinator and observer and followed a test guide (shown in Appendix A) as orientation.

Each individual test session had the following steps:

- Welcome of the user and brief presentation of the project, including its objectives and operation;
- Filling out, by the user, of a consent form for the collection, storage and use of audiovisual data;
- Filling out, by the user, of an initial questionnaire, aimed at its demographic profiling;
- Demonstration, by the test coordinator of the general functionality of the prototype, including navigation through the menus, selection of elements in the AR environment and the manipulation (pan and zoom) of the charts;
- Free trial of the prototype by the user;

- Execution of the two test tasks, in a random order (the order was determined by a coin toss by the Test Coordinator);
- Filling out, by the user, of an final questionnaire, aimed at registering the experience and opinion of the user regarding the prototype and the execution of the test tasks (Appendix B).

With consent of the users, some photos were captured during the tests.

For the assessment of the prototypes' effectiveness, two tasks were chosen, together with LNEC, to be integrated in the tests. These tasks encompass the use of relevant functionalities of the prototype and correspond to realistic scenarios of activities that a typical user can find during its every-day work.

The first task (Task A) was described to the users as follows:

> *Determine if the maximum value of the Absolute Radial Displacement measured in Position 1 of the Plumbline FPD3 is bigger or smaller than 30 mm.*

The second task (Task B) was defined as follows:

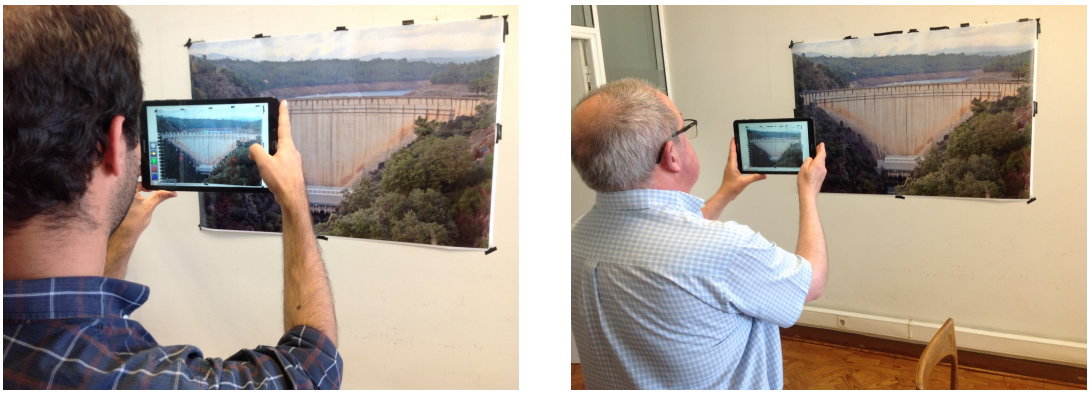
> *Determine the designation of the geodetic mark that is situated closer to the GNSS receiver located at the central point of the top of the dam.*

The first task was designed to evaluate the connection between the different functionalities of the application, namely the link between the augmented reality environment and the 2D chart environment. It required that the user turned on the visibility of the correct sensor type (plumblines), located and selected, in the augmented reality environment, the area where the sensor was located, selected the appropriate sensor in the detail window, and used the fullscreen charts in order to check the values of the chart line corresponding to the correct plumbline position.

The second task was designed to evaluate the usability and visibility of the interface in a simple and quick verification of a sensors' position. This type of task should be the most common during the inspection process and therefore the speed at which it could be carried out was very relevant.

The initial state of the system, with which the user started the tasks, was the following:

- The application was already running;



(a) (b)

Figure 6.3: Users testing the prototype

- The tracking was already in operation;
- The sensors and other elements of the 3D model were hidden, with the exception of the GNSS equipment (which was used to check if the tracking was functioning correctly).

The set of metrics registered during the tests included both objective and subjective measurements:

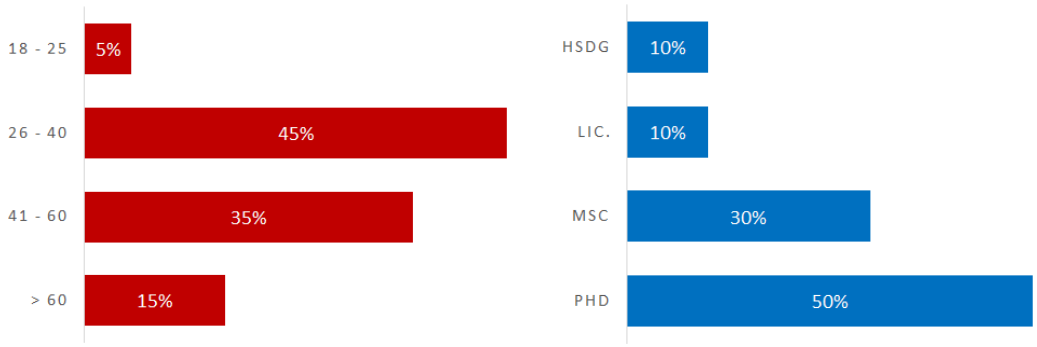
- Objective measurements:
  - Time to complete tasks A and B (in seconds);
  - Number of wrong/failed operations in each of the tasks.
- Subjective measurements:
  - Global ease of use;
  - Comfort of use;
  - Visibility and ease of sensor selection;
  - Ease of use of the detail window;
  - Ease of use of the sensor selection menus;
  - Readability of the charts;
  - Suitability of the transition process between the augmented reality environment and the full-screen charts.

6.2.2 User characterization

The tests were carried out with 20 users, the vast majority (95%) of which were part of LNEC staff. The users were 70% men and 30% women, with age distribution according to Fig. 6.4(a). The users had a very high level of education, with 90% holding a university degree ("*Licenciatura*" (Lic.), Master Degree (MSc) or Doctoral Degree (PhD)) and the remaining holding a High School Diploma Graduation (HSDG), as shown in Fig. 6.4(b).

Although most of them (95%) used multi-touch surfaces (tablets and smartphones) daily, only a very small minority (15%) had tried AR technologies previously. And from these, none had used AR in a professional scope. Instead, they had tried it mostly for entertainment (56%), in cultural visits (33%) and in training / educational activities (11%).

Most of the users were also Civil Engineers (65%) or working in the Civil Engineering area (30%) and all of these developed its professional activity in the domain of dams. Furthermore, a significant percentage of the users performed, daily (68%) or occasionally (26%), tasks related to the inspection and observation of dams.



(a) Age distribution. (b) Education.

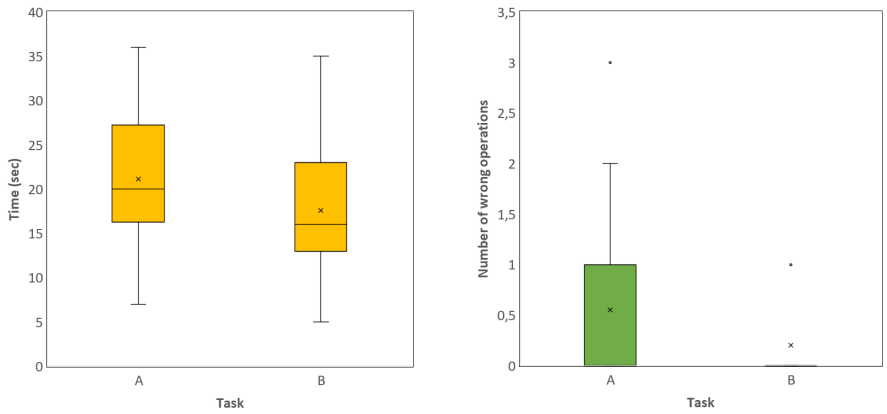
Figure 6.4: Age and level of education of users.

6.2.3 Evaluation results

Regarding the objective metrics recorded during the test, all of the users completed the tasks successfully, with completion times of less than 30 seconds (Fig. 6.5(a)). On the other hand the number of wrong/failed operations was very low in both tasks, with 70% of users performing task A with no errors, 80% performing task B with no errors and 65% of the users completing both tasks with no errors (Fig. 6.5(b)). Furthermore, the maximum number of errors registered by a single user was 3 errors in task A and 1 error in task B.

In what respects the subjective metrics, these were collected through a questionnaire, where users rated the different aspects of their experience. The questions used a Likert scale between 1 (the less favorable) and 5 (the most favorable) (Table. 6.1)

Regarding the general operation of the prototype, the vast majority of the users considered the prototype to have a friendly UI (70% rated 5 and 30% rated 4), but had a less favorable opinion regarding the comfort of use (60% rated 4 or 5 and 40% rated 3 or less).



(a) Time to complete tasks (b) Number of wrong/failed operations

Figure 6.5: Objective metrics registered during the tests. Charts include the means, medians, upper and lower quartiles, upper and lower extremes and outliers (single data points).

	$Median$	IQR
Prototype		
UI friendliness	5	1
Comfort of use	4	2
Tasks		
Easiness of Task A	5	0
Easiness of Task B	5	0
Sensors		
Ease of selection	5	1
Size suitability	5	1
Icons and colors suitability	5	0
Detail window		
Sensor selection ease	5	0
Selected area identification ease	5	0
Icons and colors suitability	5	0
Sensors menu		
Ease of use	5	0
Icons and colors suitability	5	0
Size suitability	5	0
Charts		
Ease in finding the desired values	5	1
Colors and dimensions suitability	5	0
Transition between AR and fullscreen environments		
Ease in identifying, at all times, the selected sensor	5	1
Transition speed suitability	5	0

Table 6.1: Answers to questionnaires (Median and Inter-quartile Range), regarding each criteria.

In what concerns the execution of the two tasks during the test session, in general, the users considered that both tasks were easy to complete (95% rated 5 and 5% rated 4 for task A and 85% rated 5 and 10% rated 4 for task B). This means that a small minority of users found the task A (comparing values in the chart) a little easier than task B (geodetic mark identification), although the former entails more steps than the latter. Regarding the digital model of the network of sensors, the users considered, in its vast majority, that the sensors are easy to select (60% rated 5 and 40% rated 4), have a suitable size (65% rated 5 and 30% rated 4) and use appropriate icons and colors (80% rated 5 and 20% rated 4). Similarly, users found that the Detail Window allows an easy selection of a specific sensor (90% rated 5 and 5% rated 4), an easy identification of the selected area, even when the tablet is moved (80% rated 5 and 20% rated 4) and uses adequate icons and colors (85% rated 5 and 15% rated 4)).

The users also reviewed favorably the AR Layers Menu, considering that its easy to use (95% rated 5 and 5% rated 4), uses appropriate icons and colors (90% rated 5 and 10% rated 4) and has an adequate size (90% rated 5 and 10% rated 4).

Concerning the Fullscreen Charts, that detail the evolution of the recorded values, the users considered that it was easy to find the desired values (65% rated 5 and 35% rated 4) and that the colors and dimensions of the different elements are adequate (90% rated 5 and 10% rated 4).

Furthermore, the users thought that the transition between the AR environment and the Fullscreen Charts is appropriately fast (80% rated 5 and 20% rated 4) and allows, at all times, to know which sensor is selected (65% rated 5 and 30% rated 4).

6.3 Discussion

The field testing, although scarce, allowed a general assessment of the operation of the prototype in what concerns its suitability for outdoor use. In particular, it enabled the evaluation of the capabilities of detection and tracking of the chosen AR SDK, Vuforia.

Even though the optimal situation would be the possibility of operation of the system at very large distances (more than a few hundred meters) from the structure, allowing for the user, e.g. to observe the dam from a top-down position, instead of a bottom-up position, the achieved results can be considered quite satisfactory, especially given the restrains of the project. The first of these restrains was, as mentioned in Section 5.2, the lack of distinctive features for AR tracking in the downstream face of the Cabril dam. Furthermore, the most recognizable feature of the power plant facade, the inverted ”L” shaped element, was, from the base of the dam, only completely visible at about 200 meters from the facade. This happened because newly grown vegetation interfered with the line of sight. Another important restrain was the fact that the equipment used was a low-cost, low-end tablet. This means that the use of a high-end tablet, with a better camera and superior characteristics overall, may lead to substantial performance improvements, especially in what concerns tracking.

Because at a distance of 150 meters or less from the structure of the Cabril Dam the tracking is fairly stable, the efficient and precise operation of the prototype can take place. Also, at that distance it is possible for the user to observe the full extent of the downstream face of the dam and, with it, the distribution of the sensors network located along the surface and inside the structure.

The strategy of using multiple Image Targets for each of the distinct features in the facade of the power plant also paid off. It allowed to reduce the problem of target detection at such long distances and handle, to a certain extent, the variability of luminosity conditions that can be found in the field. This was verified on multiple occasions on site, when the target detected by the prototype would change mid-session (sometimes more than once), for example when clouds covered the sun. But because, as previously mentioned, in this regard it is impossible to cover all the possibilities, the chosen approach can be considered no more than a compensation strategy for the lack of quality of the tablets' camera, instead of a true solution.

Furthermore, it was observed that the auxiliary digital notable points in the power plant facade are well aligned with reality, but the virtual sensor network is slightly misaligned with the dam structure. This can lead us to conclude that the misalignment is most likely due to the long distance between the tracking target, situated in the facade of the power plant, and the dam structure itself, along which the model is located in the augmented reality environment. This non-ideal situation, where the target is not in the structure itself, might be the reason for Vuforia miscalculating the location of the observer in relation with the structure, and its point of view.

The use of the Calibration functionality (Section 5.3.3) of the prototype allowed the correction of the superimposition of the sensor network with reality, by using as reference the leveling points and aligning them with the top of the dam. Once again this is not an ideal situation, due to the fact that, if we move the digital model from its ”correct” position, so that the user can observe it aligned with reality, there is

no guarantee that from a different observation position (e.g. the right bank of Rio Zêzere), this alignment remains.

Unlike field tests, user evaluation was carried out mainly with the purpose of understanding the suitability of the interface to tasks related to the safety control of dams. In general, the participants were very pleased with the functionality of the prototype and its UI. They found the system to be very useful and were excited about the opportunities that such a tool can present to the improvement of their work processes.

Both evaluation tasks were performed very quickly and with few or no errors. These results were unexpected, especially given the limited experience of the group of participants in respect to the use of AR technologies. Also, although the completion of task B involved just a couple of steps, task A forced the user to take advantage of almost the full range of features of the interface. It also required that the user navigated the interface in all its depth. Furthermore, both of the tasks included interaction with the AR environment.

The participants found the UI to be simple and friendly. After a brief initial explanation preceding the tests, they also successfully understood and took advantage of the possibilities offered by AR in the selection, at ”thumb-distance”, of objects in the AR environment (Fig. 5.14).

Some factors that may have helped the positive results in the tests, in what regards the speed and errors, include the fact that the vast majority of the participants worked at LNEC and were directly involved in activities related to the safety control of dams. Because of that, they were very familiar with both the symbology and the typical geometry of sensors networks used in dams. In that regard, their very high level of education may also have been a relevant factor.

The main complaint of the participants was related to the ergonomics of the equipment used for the tests. In that context, some of the users expressed their discomfort when holding the tablet, due to the limited space available in the bezel. In fact, some of the errors registered during the tests resulted from the accidental selection of the ”back”, ”home” and ”multitasking” default Android buttons. Others also reported that the use of the tablet, in the observation position (standing with the tablet at eye level), for an extended period, would possibly result in fatigue of the arms and back.

In addition to the feedback provided through the questionnaires, the users also expressed their opinion, in written or spoken form, about specific aspects of the prototype and were very proactive in giving suggestions for improvement. This valuable information, offered by highly qualified individuals, regarding the application of AR to an area where they are experts, was of extreme importance and, therefore, very welcomed.

Chapter 7

Conclusions

This work explored the application of AR technologies to the structural inspection and monitoring of large Civil Engineering structures. In particular, it was carried-out with the goal of investigating if AR technologies could be efficiently used in the scope of dam safety control, namely by offering visualization possibilities that are not accessible with traditional means.

The research was supported by the development and evaluation of DamAR, an augmented reality prototype application that can be used by inspectors in their regular activities of observation and inspection of dams. DamAR is directed at field use and can assist both Civil Engineers and Observation Technicians in visualizing the geometry of the network of sensors and easily locating a specific sensor or device in the structure of the dam. Although the prototype runs on a tablet, DamAR was developed to be easily adaptable to AR HMD's. It works by superimposing, in an AR environment, the digital model of the network of sensors to the actual structure. By selecting a sensor, the inspector can then obtain detailed information regarding the evolution of the values of horizontal displacements measured in that sensor over time. This information is shown in conjunction with the evolution of other relevant quantities related to the main structural solicitations of the dam.

By allowing the display of information *in-situ*, directly superimposed to the real structure, DamAR offers a more intuitive approach to the visualization of structural health data, in a way that is unattainable by using conventional tools.

7.1 Achievements

The greatest achievement of this work was to demonstrate that AR technologies can be efficiently used in dam safety control. This constituted the main goal of the research and was accomplished with less than ideal conditions, namely in what regards the hardware used (a low-end tablet) and the type of dam that was chosen as case study, which can be considered a very unfavorable case with regard to AR tracking, as explained in Section 5.2.

Another achievement was the successful development of a functional prototype based on real data that can effectively be used in the field. The prototype was built with a very simple and straightforward UI,

suitable even for non-tech-savvy users. It allows for the quick navigation through the different features to obtain the desired information.

DamAR also met the general requirements and expectations of the ”client” (LNEC), namely in what concerns the ability to view *in-situ* the position and geometrical configuration of the different sensors and geodetic marks and the possibility of selecting a specific sensor to detail the evolution of the displacements and other relevant values.

The strategies adopted to overcome the obstacles found in the field can be considered, by themselves, an achievement, as they were devised as a creative use of existing technological resources in order to improve its performance. These included the use of multiple Image Targets for each of the distinct features in the facade of the power plant. In fact, using a single Image Target, would have rendered the system unreliable, as even a slight change in luminosity could lead to the loss of tracking. Instead, the use of multiple targets allowed the reduction of the problem of target detection and tracking instability at such long distances by handling, to a certain extent, the variability of luminosity conditions that can be found in the field.

7.2 Future work

Although the present work demonstrated the feasibility of efficiently using AR technologies in dam safety control, it didn't address how the use of these technologies compares with the use of traditional methods. This comparison is crucial in assessing the superiority of AR-assisted methods when contrasted with conventional ones. This is an unavoidable aspect that must be considered in future work, as the medium-term development of a full-fledged AR application depends on it.

Another aspect that is worthy of improvement is the type of information that can be accessed by using the AR system and also the way that such information is presented. Indeed, although the DamAR prototype focused on showing the location of sensors for measuring horizontal displacements, and its registered values, it can be easily extended to other types of devices and data. These include sensors directed at measuring vertical displacements in the structure, extensions in the concrete or dynamic accelerations, among many others. Likewise, DamAR can be extended to show the measured values directly in the AR environment, as exemplified by the Displacement Vectors option (Figs. 5.11 and 5.13(b)). In that scope, many other useful representations can be created, including e.g. the graphical distribution of stresses and strains, the displaced configuration of the structure or even animations of the dam's modes of vibration. Other representations that can be very useful in the scope of safety control include the distribution of cracks and other structural pathology along the faces the dam or even the optimized path, through the galleries of the dam, that the inspector should take to check on a specific set of sensors.

Also the way that DamAR handles the digital models geometry should be a prime target of future work. In fact, unlike the structural measurements, that are loaded from outside the application, the geometry of the model was directly implemented using the ”Scene Editor” in Unity and therefore is ”hardcoded” in the application itself. This is an important aspect that has to be modified in future work

for DamAR to be versatile enough to be applied to other dams without the need to recompile the code. Ideally, the model should be obtained and generated automatically from data directly obtained from LNEC databases.

Although the structural measurements and other data sets are loaded from outside the application, for the development of this prototype local files were used. Future work should also focus on the important aspect of integration between the application and LNEC systems, namely through the direct acquisition of data via e.g. XML Webservices, as depicted in Fig. 5.1. This opens new interesting possibilities, namely the representation of graphical features that result from real-time data.

Finally, although DamAR was developed with both handheld and HMD devices in mind, it is yet to be tested with HMD's. This is a task that future work may also include, namely by using the AR HMD equipment recently acquired by the Visualization and Intelligent Multimodal Interfaces (VIMMI) group[1] at *Instituto de Engenharia de Sistemas e Computadores, Investigação e Desenvolvimento* (INESC-ID).

7.3 Final remarks

This work is certainly just a first step in the process of developing a full-fledged AR application that can assist Civil Engineers and Observation Technicians in dam safety control related tasks. The attainment of such application requires both a deeper analysis of the specific needs of the users, when in the field, and a greater understanding of how the users interact *in-situ*, with the AR devices. In that scope, and as previously mentioned, a comparative evaluation between AR assisted methods and traditional ones is of the utmost importance. These aspects should then be used as a basis for the development of more refined features in the AR application.

Nevertheless, this work showed that AR technologies can indeed be used in dam safety control and, furthermore, that these technologies have the potential to play a central role in the future of that activity.

The rapid progress in AR SDK's, tracking methods, the definition and overall quality of cameras and sensors, as well as the speed and efficiency of graphical processors, will undoubtedly offer the next versions of DamAR, better conditions for achieving tangible benefits in the assistance offered to the user.

[1] VIMMI, https://vimmi.inesc-id.pt/

Bibliography

[1] L. Eadicicco. A 'Smart Headset' War Between Microsoft and Google Could Revolutionize the Workplace. http://time.com/4871245/microsoft-hololens-workplace/, 2017. [Online; accessed 2017].

[2] A. T. de Castro, J. Mata, J. Barateiro, and P. Miranda. Information Management Systems for Dam Safety Control. The Portuguese Experience. *54ª Congresso Brasileiro do Concreto (CBC 2012)*, 2012.

[3] M. A.-B. Abdo. *Structural Health Monitoring, History, Applications and Future*. Open Science, 2014.

[4] R. Morais. Monitorização de deslocamentos em grandes barragens utilizando GNSS. Aplicação à barragem do Cabril. (Preliminary/Unpublished). Master's thesis, Instituto Superior de Engenharia de Lisboa, 2017.

[5] LNEC. Departamento de Barragens de Betão - Núcleo de Observação - Apresentação. http://www.lnec.pt/barragens-betao/pt/nucleo/nucleo-de-observacao/apresentacao-1/. [Online; accessed 2018].

[6] D. Pereira and F. Martins. Inspeção à estrutura e ao sistema de observação efetuada em abril de 2015. Technical report, I&D Barragens De Betão, Nota Técnica LNEC 78/2016 – DBB/NO, 2016.

[7] S. Oliveira, I. Ferreira, A. Berberan, P. Mendes, J. F. Boavida, and B. Baptista. Monitoring the structural integrity of large concrete dams: the case of Cabril dam, Portugal. *Hydro 2010, Paper 175-6*, 2010.

[8] J. Peddie. *Augmented Reality, Where We Will All Live*. Springer, 2017.

[9] M. Heilig. Sensorama Simulator. Patent No. 3,050,870. United States Patent Office, 1962.

[10] M. Heilig. Stereoscopic-Television Apparatus for Individual Use. Patent No. 2,955,156. United States Patent Office, 1960.

[11] I. E. Sutherland. A head-mounted three dimensional display. *Fall Joint Computer Conference, 1968*, 1968.

[12] PalmerTech. MTBS3D - Oculus Rift pre-order open now. GO GO GO. https://www.mtbs3d.com/phpBB/viewtopic.php?f=120&t=15522. [Online; accessed 2018].

[13] Oculus. Update on Developer Kit Technology, Shipping Details. https://www.oculus.com/blog/update-on-developer-kit-technology-shipping-details/. [Online; accessed 2018].

[14] T. P. Caudell and D. Mizell. Augmented reality: An application of heads-up display technology to manual manufacturing processes. *System Sciences, 1992. Proceedings of the Twenty-Fifth Hawaii International Conference on, Volume: ii*, 1992.

[15] M. Krueger. *Artificial reality*. Addison-Wesley, 1983.

[16] R. T. Azuma. A Survey of Augmented Reality. *Presence, vu 6, No. 4, August 1997,355-385 - Massachusetts institute of Technology*, 1997.

[17] TechCrunch. University of Washington. ARToolKit. https://www.hitl.washington.edu/artoolkit/, . [Online; accessed 2018].

[18] M. Möhring, C. Lessig, and O. Bimber. Video See-Through AR on Consumer Cell-Phones. *Proceedings of the Third IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR 2004)*, 2004.

[19] Vuforia. Announcing the 1.0 Release of the QCAR SDK! https://developer.vuforia.com/forum/news-and-announcements/announcing-10-release-qcar-sdk. [Online; accessed 2018].

[20] Microsoft. Microsoft Hololens. https://www.microsoft.com/en-us/hololens. [Online; accessed 2018].

[21] L. Motion. Our Journey to the North Star. http://blog.leapmotion.com/our-journey-to-the-north-star/. [Online; accessed 2018].

[22] CNBC. Meta attracts big investors for new augmented reality glasses. https://www.cnbc.com/2014/04/14/israels-meta-attracts-big-investors-for-new-augmented-reality-glasses.html. [Online; accessed 2018].

[23] Niantic. Pokémon GO. https://www.pokemongo.com/. [Online; accessed 2018].

[24] Newzoo. Analysis of Pokémon GO: A Success Two Decades in the Making. https://newzoo.com/insights/articles/analysis-pokemon-go/. [Online; accessed 2018].

[25] TechCrunch. The reality of VR/AR growth. https://techcrunch.com/2017/01/11/the-reality-of-vrar-growth/, . [Online; accessed 2018].

[26] R.-L. Wallin. The Use Of Virtual Reality To Increase Efficiency And Profitability In Different Industries And Functions. Master's thesis, Aalto University School of Business, 2017.

[27] N. Yabuki, K. Miyashita, and T. Fukuda. An invisible height evaluation system for building height regulation to preserve good landscapes using augmented reality. *Automation in Construction 20, 228–235. Elsevier B.V.*, 2010.

[28] W. Broll, I. Lindt, J. Ohlenburg, M. Wittkämper, C. Yuan, T. Novotny, A. F. gen. Schieck, C. Mottram, and A. Strothmann. ARTHUR: A Collaborative Augmented Environment for Architectural Design and Urban Planning. *JVRB - Journal of Virtual Reality and Broadcasting*, 2004.

[29] N. Yabuki and Z. Li. Cooperative Reinforcing Bar Arrangement and Checking by Using Augmented Reality. *LNCS 4674, pp. 50–57. Springer-Verlag, Berlin Heidelberg*, 2007.

[30] B. Thomas, W. Piekarski, and B. Gunther. Using Augmented Reality to Visualise Architecture Designs in an Outdoor Environment. *DCNET 1999 - Design Computing on the Net, Sydney*, 2007.

[31] K. Pampattiwar, A. Adiyodi, M. Agrahara, and P. Gamnani. Interior Design using Augmented Reality Environment. *International Journal of Innovative Research in Science, Engineering and Technology Vol. 5, Issue 10*, 2016.

[32] V. T. Phan and S. Y. Choo. Interior Design in Augmented Reality Environment. *International Journal of Computer Applications (0975 – 8887), Volume 5– No.5*, 2010.

[33] X. Wang. Using Augmented Reality to Plan Virtual Construction Worksite. *International Journal of Advanced Robotic Systems, Vol. 4, No. 4, ISSN 1729-8806, pp. 501-512*, 2007.

[34] A. G. R. Marto, A. A. de Sousa, and A. J. M. Gonçalves. Mobile Augmented Reality in Cultural Heritage Context: Current Technologies. *24º Encontro Português de Computação Gráfica e Interação (EPCGI 2017)*, 2017.

[35] M. Gheisari, M. F. Sabzevar, P. Chen, and J. Irizarry. An Augmented Panoramic Environment to Access Building Information on a Construction Site. *52nd ASC Annual International Conference Proceedings. Associated Schools of Construction*, 2016.

[36] K.-C. Yeh, M.-H. Tsai, and S.-C. Kang. On-Site Building Information Retrieval by Using Projection-Based Augmented Reality. *Journal of Computing in Civil Engineering, May 2012. American Society of Civil Engineers*, 2012.

[37] X. S. Lee, M. F. Khamidi, Z. S. See, T. J. Lees, and C. Chai. Augmented Reality for nDimensional Building Information Modelling - Contextualization, Customization and Curation. *22nd International Conference on Virtual Systems and Multimedia (VSMM 2016)*, 2016.

[38] S. Côté, M. Beauvais, A. Girard-Vallée, and R. Snyder. A live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings. *AVR 2014*, 2014.

[39] C.-S. Park, D.-Y. Lee, O.-S. Kwon, and X. Wang. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction 33, 61–71. Elsevier B.V.*, 2013.

[40] Y. Jiao, S. Zhang, Y. Li, Y. Wang, and B. Yang. Towards cloud Augmented Reality for construction application by BIM and SNS integration. *Automation in Construction 33, 37–47. Elsevier B.V.*, 2013.

[41] H.-L. Chi, Y.-C. Chen, S.-C. Kang, and S.-H. Hsieh. Development of user interface for tele-operated cranes. *Advanced Engineering Informatics 26, 641–652. Elsevier B.V.*, 2012.

[42] G. Schall, E. Mendez, E. Kruijff, E. Veas, S. Junghanns, B. Reitinger, and D. Schmalstieg. Handheld Augmented Reality for underground infrastructure visualization. *Personal and Ubiquitous Computing (2009) 13:281–291. Springer-Verlag*, 2009.

[43] A. H. Behzadan and V. R. Kamat. Interactive Augmented Reality Visualization for Improved Damage Prevention and Maintenance of Underground Infrastructure. *Construction Research Congress 2009. American Society of Civil Engineers*, 2009.

[44] G. Schall, E. Mendez, and D. Schmalstieg. Virtual Redlining for Civil Engineering in Real Environments. *IEEE International Symposium on Mixed and Augmented Reality. IEEE, Cambridge*, 2008.

[45] F. Liu and S. Seipel. Infrared-visible image registration for augmented reality-based thermographic building diagnostics. *Visualization in Engineering. Springer*, 2015.

[46] F. F. F. Peres, S. Scheer, Étore Funchal De Faria, and W. A. D. Rosa. Augmented Reality to Access Dam Cracks Information. *Int. Journal of Engineering Research and Applications, Vol. 6, Issue 3, (Part - 1), pp.24-28*, 2016.

[47] B. Koo, H. Choi, and T. Shon. WIVA: WSN Monitoring Framework Based on 3D Visualization and Augmented Reality in Mobile Devices. *ICOST 2009, pp. 158–165, Springer-Verlag, Berlin Heidelberg*, 2009.

[48] D. H. Shin and P. S. Dunston. Evaluation of Augmented Reality in steel column inspection. *Automation in Construction 18, 118–129. Elsevier B.V.*, 2009.

[49] V. R. Kamat and S. El-Tawil. Evaluation of Augmented Reality for Rapid Assessment of Earthquake-Induced Building Damage. *Journal of Computing in Civil Engineering - September/October 2007. American Society of Civil Engineers*, 2007.

[50] C. Papachristos and K. Alexis. Augmented Reality–enhanced Structural Inspection using Aerial Robots. *2016 IEEE International Symposium on Intelligent Control (ISIC). IEEE, Buenos Aires*, 2016.

[51] A. Silva, H. Galhardas, J. Barateiro, H. Matos, J. Gonçalves, and E. Portela. Data Analysis Features of the GESTBARRAGENS System. *International Conference on Innovative Views of .NET Technologies (IVNET)*, 2006.

[52] A. Silva, H. Galhardas, J. Barateiro, and E. Portela. O Sistema de Informação GestBarragens. *Conferência Barragens: Tecnologia, Segurança e Interacção com a Sociedade*, 2005.

Appendix A

Test Guide

This appendix includes the test guide, used by the observer/coordinator during the user evaluation of the prototype.

Guião de Testes DamAR

O que se vai avaliar:

Os testes têm como principal objetivo avaliar a usabilidade de uma interface de utilizador em ambiente de realidade aumentada, em particular a sua adequabilidade ao uso em tarefas de controlo da segurança de barragens.

Sistema a avaliar:

O sistema que se pretende avaliar consiste no protótipo de uma aplicação de realidade aumentada para *tablet*, dirigida à visualização, sobreposta à realidade, de diferentes grandezas e componentes de sistemas de monitorização da segurança da saúde estrutural de barragens.

A interface de realidade aumentada permite ao utilizador a visualização do modelo tridimensional de uma rede constituída por diferentes tipos de sensores distribuídos pelo interior da barragem (fios de prumo), pelo paramento de jusante (marcas geodésicas) e ponto central do coroamento da estrutura (GNSS) (respetivamente representados a vermelho, azul e verde na Fig.1).

Fig. 1: Representação, num ambiente de realidade aumentada, dos sensores e dispositivos de medição destinados à determinação de deslocamentos horizontais na estrutura da barragem

Quando o utilizador toca num ponto específico da barragem, é mostrada uma janela com o detalhe dos sensores existentes na área circundante ao ponto selecionado (Fig.2). Esta janela permite a seleção mais precisa do sensor pretendido.

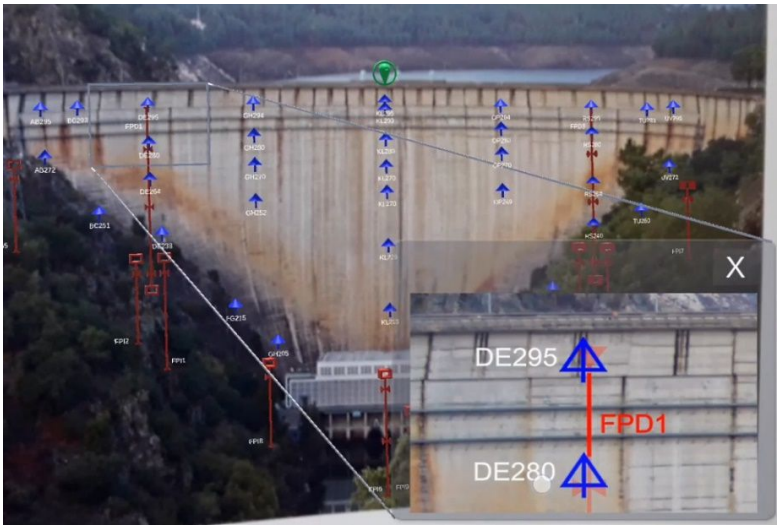


Fig. 2: Janela com pormenor de zona selecionada

A seleção de um sensor específico através de toque sobre a janela, faz surgir um conjunto de gráficos em ecrã inteiro (Fig.3), no qual é representada a evolução ao longo do tempo das grandezas relevantes (deslocamentos em diferentes posições do sensor, cota de água e temperatura).

Estes gráficos podem ser aproximados/afastados ou deslocados, respetivamente através de movimentos de *pinch/zoom* com dois dedos e de toque e arrastamento com um dedo.

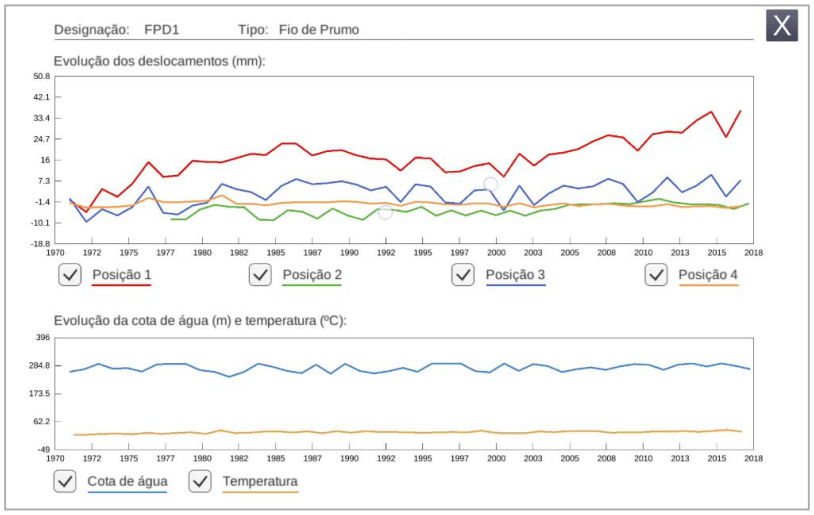


Fig. 3: Gráficos em ecrã inteiro

Adicionalmente a interface permite controlar, através de um menu existente no canto inferior esquerdo, os tipos de sensores e dispositivos que são apresentados no ambiente de realidade aumentada (Fig.4).

Fig. 4: Menu para escolha dos sensores e dispositivos a apresentar

Ambiente:

Os testes irão realizar-se numa das salas de reuniões do Departamento de Barragens de Betão (DBB) do Laboratório Nacional de Engenharia Civil (LNEC) e, caso seja necessário, em outros espaços do LNEC.

O conjunto de equipamentos e materiais a serem utilizados nos testes incluem: um tablet Android que correrá a aplicação de realidade aumentada, um tablet Apple IPad, que será utilizado pelos utilizadores para responder aos questionários e um poster com a imagem da Barragem do Cabril que permitirá simular a representação de realidade aumentada sobre a barragem real.

Metodologia:

Os testes incluirão a realização individual, por parte dos utilizadores de cada uma das tarefas detalhadas na secção seguinte. Será solicitado que estas sejam realizadas sequencialmente, sendo fornecida pelo Coordenador do Teste a ordem, aleatória, de execução.

A metodologia de realização dos testes pressupões as seguintes etapas realizadas individualmente:

1. Acolhimento ao utilizador, com apresentação do projeto, incluindo seus objetivos e funcionamento (2 min);
2. Preenchimento, pelo utilizador, de um formulário de consentimento para a recolha, armazenamento e uso de dados audiovisuais (2 min);
3. Preenchimento, pelo utilizador, de um questionário inicial para registo do perfil de utilizador e suas características demográficas (3 min);
4. Demonstração, pelo Coordenador do Teste, das funcionalidades do protótipo, incluindo a navegação pelos menus, seleção de elementos no ambiente de realidade aumentada e manipulação dos gráficos (4 min);
5. Experimentação livre do protótipo pelo utilizador (2 min);
6. Execução, pelo utilizador, das 2 tarefas, aleatoriamente indicadas pelo Coordenador do Teste (tempo máximo 8 min);

7. Preenchimento, pelo utilizador, de um Questionário Final para registo da sua experiência e opinião sobre o teste realizado (4 min).

A duração total não deverá ultrapassar os 25 minutos.

Se o utilizador der o seu consentimento para tal, os testes serão filmados, com recolha de áudio e vídeo, sendo também tiradas algumas fotografias.

Tarefas:

As tarefas seguintes serão apresentadas ao utilizador sequencialmente e por ordem aleatória:

A. Determinar se o valor do deslocamento máximo no fio de prumo FPD3, na Posição 1, é superior ou inferior a 30 mm.

B. Determinar a designação da marca geodésica que se encontra mais próxima do recetor GNSS localizado no ponto central do coroamento (topo) da barragem.

O estado inicial do sistema, com o qual o utilizador iniciará as tarefas, será o seguinte:

- A aplicação já estará em funcionamento;
- O *tracking* já estará em funcionamento;
- Os sensores e restantes elementos do modelo estarão ocultos, à exceção do GNSS (este permitirá ao observador verificar se o *tracking* foi efetuado com sucesso).

Métricas:

Medidas objetivas:

- Tempo de realização das tarefas A e B (segundos);
- Número de operações erradas em cada uma das tarefas.

Medidas subjetivas (questionário final em anexo):

- Facilidade global;
- Comodidade de utilização;
- Visibilidade e facilidade de seleção dos sensores;
- Facilidade de utilização da janela de pormenor;
- Facilidade de utilização dos menus de seleção de sensores;
- Facilidade de leitura dos gráficos;
- Adequabilidade da transição entre o ambiente de realidade aumentada e os gráficos em ecrã inteiro.

Appendix B

Test Questionnaire

This appendix includes the final questionnaire that was filled out by the participants of the tests.

TÉCNICO LISBOA

Questionário Final

Este questionário tem uma duração aproximada de 4 minutos, e tem como objetivo registar a sua opinião sobre o teste que acabou de realizar. Toda a informação dada será tratada de forma confidencial, e será usada unicamente para fins académicos. Agradecemos a sua disponibilidade e tempo para participar.

O protótipo...

(Marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Tem uma interface amiga do utilizador	○	○	○	○	○
É cómodo	○	○	○	○	○

Relativamente às tarefas de teste...

(Marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Foi fácil realizar a tarefa A *(Comparar valores em gráfico)*	○	○	○	○	○
Foi fácil realizar a tarefa B *(Identificar marca geodésica)*	○	○	○	○	○

Os sensores sobrepostos à barragem...

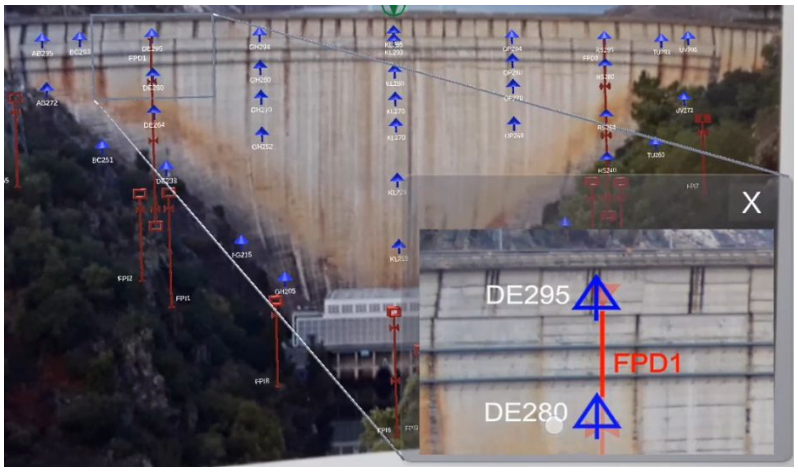
(Marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
São fáceis de selecionar	○	○	○	○	○
Possuem uma dimensão adequada	○	○	○	○	○
Têm ícones e cores adequados	○	○	○	○	○

TÉCNICO LISBOA

A janela com o pormenor da zona selecionada...

(Marque apenas uma opção em cada linha)



	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Permite a escolha fácil de um sensor específico	○	○	○	○	○
Permite identificar facilmente a zona selecionada, mesmo quando se move o tablet	○	○	○	○	○
Tem ícones e cores adequados	○	○	○	○	○

O menu para seleção dos sensores a mostrar...

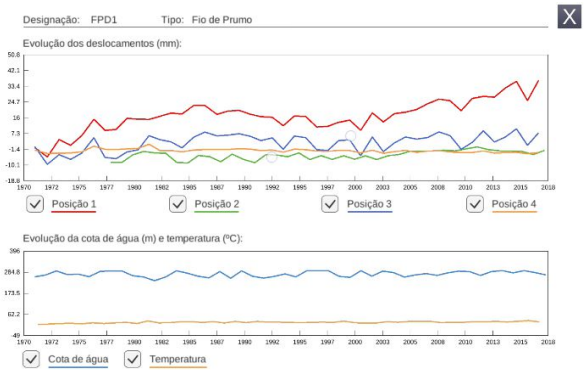
(Marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
É fácil de utilizar	○	○	○	○	○
Tem ícones e cores adequados	○	○	○	○	○
Possui uma dimensão adequada	○	○	○	○	○

TÉCNICO LISBOA

Nos gráficos de deslocamentos, temperaturas e níveis de água...

(Marque apenas uma opção em cada linha)



	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Foi fácil encontrar os valores desejados	○	○	○	○	○
As cores e dimensões dos diferentes elementos são adequadas	○	○	○	○	○

A transição entre o ambiente de realidade aumentada e os gráficos em ecrã inteiro...

(Marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Permite saber sempre qual o sensor que foi selecionado	○	○	○	○	○
É suficientemente rápida	○	○	○	○	○