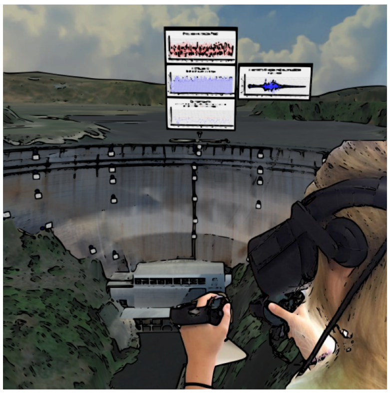

Dam Health Monitoring with Virtual Reality

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Thesis to obtain the Master of Science Degree in

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Abstract

Structural Health Monitoring (SHM) is an area that is present in various engineering fields and aims to follow and evaluate in real-time the strength of structures, to detect failures as soon as possible. Usually done through traditional methods, it still is necessary to explore the integration of immersive technologies, such as Virtual Reality (VR) or Augmented Reality (AR), in SHM tasks, being that the focus of this work.

In particular, this work aims to study the consequences and the utility of applying VR in data analysis related to dam safety control. For that, this dissertation included the study of related work involving the application of VR in different fields of the industry of Architecture, Engineering, and Construction, namely in structural engineering, as well as in dams.

A VR prototype, called VRCabrilAnalysis, was created. This prototype allows the visualization of data related to the safety of the Cabril Dam, as well as the interaction with its sensors. This prototype was created to contribute to the development of applications that integrate immersive technologies in the SHM of dams. The usability and applicability of VRCabrilAnalysis in the SHM field were evaluated through evaluation sessions with real users. This was done to gather data that supports this research, being later concluded that VR can be applied in dam safety control.

Keywords

Virtual Reality; Digital Shadow; Immersive Environments; Structural Health Monitoring; Dam Analysis; Damage Evolution

Resumo

A Monitorização da Integridade Estrutural (SHM) é uma área que está presente em vários campos da engenharia e visa acompanhar e avaliar em tempo real a robustez de estruturas, de modo a detetar falhas o mais cedo possível. Feita geralmente através de métodos tradicionais, ainda é necessário explorar a integração de tecnologias imersivas, tais como Realidade Virtual (VR) ou Realidade Aumentada (AR), nas tarefas de SHM, sendo esse o foco deste trabalho.

Em particular, este trabalho visa estudar as consequências e a utilidade de aplicar VR na análise de dados relacionados com o controlo de segurança de barragens. Para isso, esta dissertação incluiu o estudo de trabalho relacionado envolvendo a aplicação de VR em diferentes campos da indústria da Arquitetura, Engenharia e Construção, nomeadamente na engenharia de estruturas, bem como em barragens.

Um protótipo VR, chamado VRCabrilAnalysis, foi criado. Este protótipo permite a visualização de dados relacionados com a segurança da Barragem do Cabril, bem como a interação com os seus sensores. Este protótipo foi criado para contribuir para o desenvolvimento de aplicações que integram tecnologias imersivas no SHM de barragens. A usabilidade e aplicabilidade do VRCabrilAnalysis no campo de SHM foram avaliadas através de sessões de avaliação com utilizadores reais. Isto foi feito para obter dados que suportam esta pesquisa, sendo concluído posteriormente que VR consegue ser aplicada no controlo de segurança de barragens.

Palavras Chave

Realidade Virtual; Digital Shadow; Ambientes Imersivos; Monitorização da Saúde Estrutural; Análise de Barragens; Evolução de Danos

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Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AEC	Architecture, Engineering, and Construction
AR	Augmented Reality
BIM	Building Information Modeling
CAD	Computer-Aided Design
CGI	Computer-Generated Imagery
CPU	Central Processing Unit
CSV	Comma-Separated Values
DAD	Discharge Abstract Database Metadata
Ext.	Exterior
FBX	Filmbox
FOV	Field of View
FPS	Frames per Second
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite System
GPU	Graphics Processing Unit
HMD	Head-Mounted Display
HSDG	High School Diploma Graduation
Int.	Interior
INESC	*Instituto de Engenharia de Sistemas e Computadores, Investigação e Desenvolvimento*

IQR Interquartile Range

IVR Immersive Virtual Reality

Lic. *Licenciatura*

LNEC National Laboratory for Civil Engineering / *Laboratório Nacional de Engenharia Civil*

MR Mixed Reality

MSc Master Degree

MVC Model-View-Controller

NGA Applied Geodesy Unit / *Núcleo de Geodesia Aplicada*

NMMR Modelling and Rock Mechanics Unit / *Núcleo de Modelação e Mecânica das Rochas*

NO Monitoring Unit / *Núcleo de Observação*

NURBS Non-uniform rational B-spline

OBJ Object File

OFF Object File Format

PhD Doctoral Degree

PLY Polygon File Format

PMU Physical Mock-up

PNG Portable Network Graphics

POV Point of View

SHM Structural Health Monitoring

UI User Interface

VM Virtual Model

VMU Virtual Mock-up

VR Virtual Reality

XLS Microsoft Excel Spreadsheet

1

Introduction

Contents

Structural Health Monitoring (SHM) is the real-time evaluation of a physical structure and the materials that compose it. It aims to detect failures as early as possible, minimizing risks and ensuring safety [Balageas et al., 2010]. It is traditionally done through the use of sensors, measurement techniques, and data processing. In particular, monitoring the structural health of dams is crucial to get information about their longevity and safety, as well as to detect damaging behaviors as soon as possible[1].

The SHM area has benefited a lot from emerging technologies, which are crucial in data collection and analysis. This includes technologies such as certain types of sensors (strain gauges, fiber optic sensors, and thermopile laser sensors) [Brownjohn, 2007], radars, acoustic emission technologies, and deep learning applications [Tao, 2019]. With similar goals, immersive technologies can be applied in the SHM area.

Immersive technologies are the technologies that have the goal of reducing the discrepancy between the physical world and the virtual content [Suh and Prophet, 2018]. One example of immersive technology is Virtual Reality (VR), a technology that provides an immersive human-computer interaction experience, enabling the users to feel like being inside an artificial world that responds to their movements and actions.

According to the reality-virtuality continuum [Milgram et al., 1995], VR is the technology with the highest proportion of virtual components in its environment [Billinghurst et al., 2001], being that environment addressed as purely virtual. Technologies with real components in their environment are, for example, Augmented Reality (AR) technologies, which involve the direct or indirect visualization of the real world, augmented with Computer-Generated Imagery (CGI). AR is included in Mixed Reality (MR), which consists of any technology that includes both real and virtual objects in the same environment [Rokhsaritalemi et al., 2020].

1.1 Motivation

There are numerous applications of VR, ranging from video games to job simulations. One of its uses is to train difficult and dangerous tasks such as simulations of surgery, flight, and natural disaster management (like floods [Padilha et al., 2019] or fires [Vichitvejpaisal et al., 2016]), by simulating them inside a virtual environment, ensuring the safety of the participants. Likewise, VR can be used in the Architecture, Engineering, and Construction (AEC) industry, namely in practical training sessions, simulations of construction performance, construction safety evaluations, and design tasks.

It is possible to apply VR in Immersive Analytics, which is a field that uses immersive technologies combined with data visualization, visual analytics, and human-computer interaction. Immersive Analyt-

[1] Monitoring of Dams - Digitex Systems, `https://www.digitexsystems.com/dams`, January 2022

ics provides the user with the necessary means to facilitate data understanding and decision-making, creating a connection between the data, the users, and the analysis tools [Malik et al., 2005].

Despite the many applications of VR over the years, its integration into the SHM area still needs to be further explored. In particular, incorporating VR technologies in dam health monitoring could offer substantial benefits, given the large dimensions of dams, which can make on-site analysis difficult. It could also ensure the safety of the engineers, since the tasks are done indoors and therefore don't involve the risks that are associated with the on-site analysis. Other benefits of this integration could come from the use of VR for immersive analytics data related to dam safety.

The use of VR for the visualization of data concerning the safety of dams can show potential advantages when compared with the use of traditional means, particularly when combined with a realistic digital model. It can allow the dam engineers to perform tasks of dam safety analysis inside a distraction-free environment. It can also provide an immersive situated analysis, that frames the data within the visual context of the dam (the examined object). Likewise, it can also improve the understanding of the spatial arrangement and size relationship between objects.

1.2 Objectives

This work was done in collaboration with the National Laboratory for Civil Engineering / *Laboratório Nacional de Engenharia Civil* (LNEC). It explores the application of immersive analytics in the SHM field. It is focused on understanding how it could be helpful in SHM tasks as well as in analyzing its advantages and disadvantages. To achieve these goals, this work presents related work concerning several examples of the integration of VR on the AEC industry, and more precisely on structural engineering, and cases of VR being applied to dams.

The main objective of this work is to contribute to the development of VR applications for use in dam safety control. For this, a VR prototype, called VRCabrilAnalysis, was created as a proof of concept and will serve as a starting point for future work. For carrying out the development of VRCabrilAnalysis, it was necessary to identify, analyze and establish its requirements, which was done through meetings with the LNEC staff.

A model of the Cabril dam was created, using a point cloud created from laser scans performed by LNEC at the Cabril dam, as well as a texture created by [Baptista, 2016], that consisted of various images of the dam that were orthorectified. Several approaches were taken to build the model of the dam, with different algorithms being tried for sampling the point cloud, creating the triangles, and defining the UV mapping (to correctly apply the texture).

The prototype contains a coherent representation of Cabril's surrounding area. The texture was made by merging several screenshots with an orthographic projection, taken from a Google Maps satellite view of Cabril. The mesh was created from a Basemap[2] using satellite data from Google and elevation data from a specific server. A surrounding area was necessary to provide users with sufficient levels of immersion while performing the tasks.

Different data visualization idioms were studied to determine which was the most suitable way to represent the data measured by the sensors, as well as different features for interacting with the data. A suitable representation of the data was crucial to make the users able to carry out tasks in an effective way.

One of the objectives of this work is to evaluate the prototype by testing it, for collecting data regarding the effectiveness and usefulness of incorporating VR into dam safety analysis. The evaluation phase was carried out through individual user test sessions, with the users giving information and feedback about the general usability of the prototype, as well as performing tasks of dam safety analysis there. Both the computer and the VR equipment were from *Instituto de Engenharia de Sistemas e Computadores, Investigação e Desenvolvimento* (INESC).

1.3 VRCabrilAnalysis

A VR prototype, called VRCabrilAnalysis, was developed as a proof of concept. This proof of concept prototype will be a starting point for the development of an effective VR application for the SHM of dams. VRCabrilAnalysis applies immersive analytics in the SHM of dams, by using line charts integrated with a virtual environment. This can help dam engineers in the analysis of data concerning the safety of the Cabril dam (Figure 1.1(a)).

The requirements for the prototype were established together with the LNEC staff through meetings. The prototype included different VR locomotion techniques, allowing the users to move around the vir-

(a) The Cabril dam in real life

(b) Representation of the Cabril dam in VRCabrilAnalysis

Figure 1.1: The Cabril dam and its representation in VRCabrilAnalysis

[2]A Basemap is a layer containing geographic information that can be transmitted to other dataset layers above it, giving the necessary information to create a model that visually represents a certain location [Wieczorek and Delmerico, 2009]

tual environment. This virtual environment contained a model representing the Cabril dam (which was created from the point clouds provided by LNEC), as shown in Figure 1.1(b), along with its surrounding area. The model also contained different sensors with which the users could interact, by selecting them through Raycasting. When interacting with a specific sensor, the users should be able to view and analyze the sensor's registered data, as well as its description and information. This prototype contained different interaction features (such as the zoom-in/zoom-out, the pan feature, and the brush feature to select an interval of data) that helped in the analysis of the line charts.

1.4 Evaluation

VRCabrilAnalysis was evaluated to get results that help in the exploration of the consequences of applying immersive analytics in the SHM field. The evaluation sessions, which took place in LNEC, were done individually for each participant, and their methodology consisted of the collection of each participant's demographic information, followed by the participant learning about the prototype and freely using it, and using the prototype to perform two tasks related to SHM of dams after that. It ended with the participant giving feedback about the prototype and suggestions on possible changes to be made to the prototype in the future.

1.5 Document Structure

The current chapter, which is Chapter 1 (Introduction) introduces the general idea of this work, as well as its motivation and objectives. Chapter 2 (Related Work) presents related work concerning different examples of applications of VR in AEC, with a stronger focus on VR applied in structural engineering and VR applied in dams. Chapter 3 (VRCabrilAnalysis) describes the raised requirements, the concept, the architecture and the consequent approaches for the development of the prototype. Chapter 4 (User Evaluation) describes the evaluation methodology that was used to gather the results of this study and presents and discusses those results. Chapter 5 (Conclusions) presents the general conclusions that can be taken from this work, more precisely what was achieved with it, the limitations that were faced, and the aspects that were considered for future work.

2

Related Work

Contents

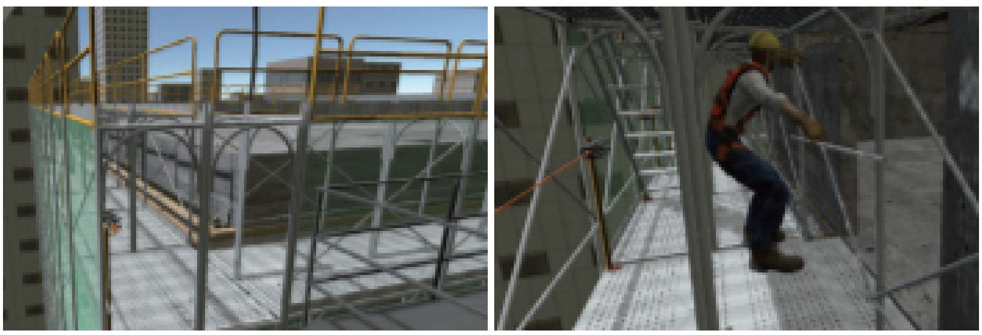
VR provides an experience in which the user is integrated into a virtual world. It is described by [He, 2020] as an organic combination between immersion, interaction, and imagination, generating a Three-Dimensional (3D) environment with an immersive experience. It is mainly used in the medical, military, aerospace, entertainment, and AEC industries.

2.1 Virtual Reality in AEC Industry

VR has been applied in the immersive virtual training of certain tasks and in applications to allow workers to coordinate construction sites without needing to be on-site. Using VR to train AEC workers can be a great improvement when it comes to safety. The main reason comes from the fact that the AEC industry has the worst fatality and injury statistics [Hafsia et al., 2018] and, therefore, security and health issues are of utmost importance there.

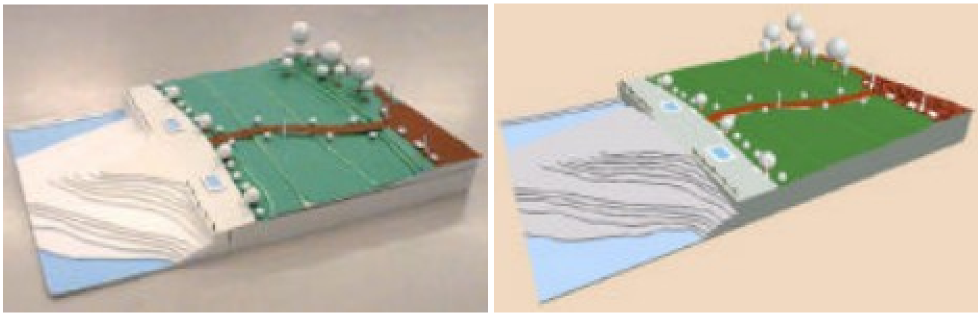
It is strictly necessary to correctly perform every task in the AEC industry, as any mistake can cost a person's physical integrity or even a life. Having this aspect in mind, construction companies have training sessions consisting of theoretical and practical classes for the training of construction workers. Since theoretical lessons can represent incomplete training, practical lessons are essential to ensure a full understanding of how to perform everything correctly. However, practical lessons can be risky, since they are done on-site and require the use of diverse construction tools [Tan et al., 2022]. To hinder the inconveniences associated with the practical lessons, several VR applications were developed to offer an immersive training environment that ensures the safety that the practical lessons on-site can't provide.

VR training tools for AEC are not new. For example, [Hadipriono, 1996] developed four VR models to be used as training tools in the AEC industry as early as 1996. Those models encompassed the training of specific tasks and simulation of construction methods. The fact that those applications were



(a) **(b)**

Figure 2.1: VRIES reproduction of hazardous scenarios [Wu et al., 2020]



(a) The PMU **(b)** The VM

Figure 2.2: A PMU and its respective VM [Seigo et al., 1999]

developed 27 years ago shows how present the AEC industry has been in the development of VR applications over the years, as well as how important it has always been to train civil engineers in a safe immersive environment. To study the uses of VR in AEC, [Al-Adhami et al., 2018] proposed workflows for Immersive Virtual Reality (IVR) applications in construction, visualization, and building performance analysis, by conducting an experiment based on three types of data, which were Four-Dimensional (4D) construction simulation in VR, rapid generation of the VR scene, and airflow visualization of VR.

Regarding immersive training environments in the AEC industry, [Hafsia et al., 2018] developed a VR application to train construction workers on the formwork stabilization task. This application offers both visual and auditory immersion, inside an immersive and interactive environment. Another example of this was VRIES (Figure 2.1), a VR interactive education system developed by [Wu et al., 2020], that was divided into four categories. The categories were environmental hazard identification, equipment safety inspection, unsafe behavior correction, and frequent accidents. The system included 17 different safety scenes and presented pre-test and post-test modules to test the effectiveness that VRIES had in hazard identification training.

Traffic engineering is another AEC field that has benefited from the use of VR, as demonstrated by [Uhr et al., 2019], who designed and developed an interactive VR application for the visualization of multidimensional roadworks data. This application, which offers interactive visualizations that assist traffic engineers in their work, had its development motivated by the impossibility of simultaneously representing all the essential information for the coordination of construction sites in Two-Dimensional (2D) visualizations. Likewise, urban planning and design is another AEC field where applying VR can offer advantages for its improvement. Here, the use of VR technology can provide a wide range of emulations that allow the users to verify the impact a certain project has on its surroundings [He, 2020].

Physical Mock-up (PMU), as shown in Figure 2.2(a), is the conventional way of presenting construction works, by modeling the project in a physical model, with materials such as plastic, paper, or cardboard. Since this representation is costly and time-consuming, other alternatives can be used, such

(a) The VR environment displaying the measurements of a model

(b) Interaction between the user and the environment

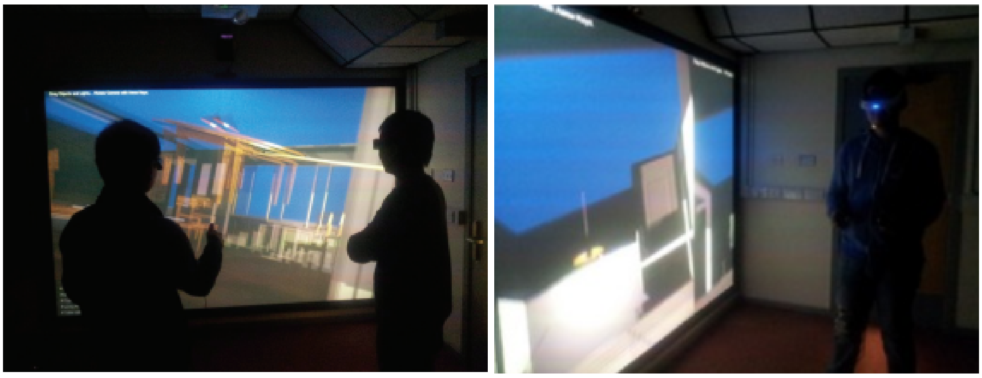
Figure 2.3: The VR-integrated workflow in BIM-based projects [Zaker and Coloma, 2018]

as the development of a Virtual Mock-up (VMU), which is the representation of the building project in a virtual environment [Maing, 2012]. Likewise, another way to present construction works is through the creation of a Virtual Model (VM) (Figure 2.2(b)), which consists of a set of digital models with information about a project, and has been present in the development of several VR applications. Given the benefits that VMs present when compared with PMUs, along with the utility VR has for accurately simulating reality, [Seigo et al., 1999] created in 1999 a VM with VR technology to be used as a practical tool.

Building Information Modeling (BIM) is a methodology that digitally creates a VM of a certain construction project, the building information model [Azhar, 2011]. It is seen as a revolutionary development in the AEC industry, showing benefits in the whole life cycle of a project, such as helping workers understand and visualize complex designs, and ensuring an effective collaborative workflow in design disciplines. It has become the standard tool in AEC for the communication of construction and design details in projects. Despite their advantages, BIM models lack when it comes to visual effects and so, to improve the effectiveness of the 3D visualization, it is useful to integrate them with VR. This is done by combining data models with VR images, which can ensure an immersive virtual experience and therefore improve the planning of the workspace [Getuli et al., 2020].

By integrating BIM with VR, a better understanding of the objectives of the project can be achieved, when compared with only using BIM [Alizadehsalehi et al., 2021]. It can also improve communication and collaboration among the project participants, thanks to the application of Collaborative Virtual Environments, which are distributed VR systems that allow multiple users in different physical locations to interact with each other in the same virtual environment [Churchill and Snowdon, 1998].

To study the benefits of integrating BIM with VR in the AEC industry, [Tariq et al., 2019] used Revit Architecture to create a model of a hospital, concluding that this integration could be excellent for decision making. With the same goal, [Zaker and Coloma, 2018] defined a virtual environment that allows multiple users to collaboratively visualize a BIM model in a VR environment (Figure 2.3). Another example of



(a) The public activated 3D view of the VR environment

(b) The personal HMD view

Figure 2.4: VR environment for highlighting fire evacuation plans during the life cycle of the building [Wang et al., 2014]

this was a study conducted by [Lin et al., 2020], that used Lumion to simulate the construction process of a bridge. [Liu et al., 2020] stated an example of a project that imports a complete BIM model into the VR software to conduct collision inspections. Another example of this integration is a framework proposed by [Boton, 2018] that allows the interaction of users in a VR-based collaborative BIM 4D simulation.

This integration can also be applied to natural disaster management. An example of this is a project developed by [Wang et al., 2014], that uses BIM as a source of data to build a VR environment for highlighting fire evacuation plans during the life cycle of the building (Figure 2.4). It can also be useful for optimizing signage design. [Motamedi et al., 2017] proposed the use of an updated BIM model of a building, using a graphical engine to simulate the movement of pedestrians around it inside the virtual environment.

The integration of BIM with VR can also offer benefits for designers, helping them make effective decisions to reduce costs. [Natephra et al., 2017] created BIM-based lighting design feedback (BLDF), a prototype that integrates BIM with an interactive and immersive VR environment. This provides realistic visualizations of lighting conditions and an effective analysis of the consumption of energy in the lighting design. To aid the decision-making in construction planning and maintenance, [Sampaio et al., 2010] developed a prototype that integrates a VR system with a computer application that was implemented in Visual Basic. This prototype allows the visualization and analysis of the material information of a certain physical model.

Exporting the BIM model in a VR-compatible engine, to integrate it with VR, is an error-prone process where information loss may occur. This makes it necessary to have additional processes of model alteration, which may cause information latency. To combat this issue, [Du et al., 2018] developed BIM-VR Real-time Synchronization (BVRS), a data transfer protocol that allows the information to be updated in real-time in VR displays. It is also possible to integrate VR with both BIM and Computer-Aided Design (CAD), which is the use of certain software to help the workers in the design process [Mark et al., 2008]. For example, [Goulding et al., 2014] developed Web-Based Game-Like VR Construction Site Simulator (WWGVRSS), an interactive and collaborative system that uses a CAD interface and a web-based VR interface, to support an online BIM platform for the integration of projects in AEC.

Besides VR, MR can also be integrated with BIM. One example of this is an MR application developed by [Raimbaud et al., 2019], that uses the 3D BIM model of a building combined with real data from drone videos. It provides interactions to the users such as moving around the model (through the simulation of a drone flight) and seeing drone videos depending on the point of view at that moment. This allows the workers to perform construction supervision outside the construction site. AR is also used to integrate with BIM, with several examples presented in a study conducted by [Wang and Love, 2012].

2.2 Virtual Reality applied in Structural Engineering

Structural Engineering is the field of engineering that focuses on designing, monitoring, and ensuring the safety of structures such as bridges, dams, viaducts, and buildings. This involves areas such as structural analysis and structural design, among others [Chen and Lui, 2005]. This field can benefit from VR in various aspects, given the deep immersion that the VR systems provide. In particular, Head-Mounted Display (HMD) VR presents significant benefits in performance when compared with desktop VR and presents a similar efficiency when compared with high-end VR systems. Those effects were studied by [Huang, 2018], who therefore concluded that HMD VR presents advantages over desktop VR when it comes to making it easier for users to collaboratively learn and perform tasks.

Structural analysis is the field of structural engineering that has the goal of analyzing and estimating how a structure or a member of a structure behaves when subjected to certain conditions [Hibbeler and Tan, 2006]. The main advantage of applying VR in structural analysis is the risk-free immersive scenario that can be provided. This integration can allow the structure inspectors to analyze every part of a certain structure while being safe from any hazard, as well as reach parts of the structure that are impossible to reach physically. It can also help to deal with the complexity present in the visualization of implicit structural knowledge [Tan et al., 2022].

Regarding the integration of VR in education in the field of structural engineering, [Wong and Humayoun, 2022] developed San Francisco State University's (SFSU) Virtual Reality Engineering Program (VR Engine). The objective of VR Engine is to help structural engineering students in comprehending structural design and theory through the use of VR, since these concepts are naturally abstract and therefore difficult to visually perceive. It also has the goal of preparing and practicing the structural engineering

Figure 2.5: User performing a bridge inspection with ImSpector [Veronez et al., 2019]

students for the tasks of post-hazard event reconnaissance, evaluation, and rebuilding. Likewise, [Chou et al., 1997] studied the use of VR to create virtual learning environments for teaching structural analysis. In particular, VR can be useful to learn about structural analysis, given the presence of highly abstract concepts in that field.

The inspection by observation of bridges and viaducts presents some barriers, such as the inaccessibility to be present in the structure itself. To combat this, remote sensors on unmanned aerial vehicles [Yao et al., 2019] and laser scanners [Leonov et al., 2015] are used to perform mapping techniques. This enables a more efficient analysis of the structure and therefore allows the generation and visualization of 3D models of the structure. Those models can be integrated into virtual environments. Based on this integration, [Veronez et al., 2019] developed ImSpector (Figure 2.5), a VR system that enables collaborative work and uses 3D models generated by remote sensors. This allows the user to remotely perform field tests during bridge and viaduct inspections, while immersed in a virtual environment that represents him being on-site.

Field workers in the AEC industry often perform outdoor tasks such as network planning and inspection of underground infrastructures, needing to refer to the data in Geographic Information Systems (GIS) and to do the process of Redlining, which is manually annotating the data on-site, either on paper or on a laptop. By performing it on a laptop, the efficiency of the process can be improved, since it becomes possible to directly consult the GIS, which uses 2D models to represent the geographic data. There are ways to manage complex 3D models in Redlining and for this, [Schall et al., 2008] developed a mobile AR system capable of supporting virtual Redlining. Regarding the use of VR for the inspection of underground infrastructures, [Attard et al., 2018] proposed a robotic system composed of three modules, that uses VR technology to render the tunnel wall structures.

In particular, SHM is the process of obtaining accurate and updated information regarding the condition and strength of a certain structure [Mesquita et al., 2016]. It is a process that can be divided into five main activities, which are the definition of the SHM strategy, the installation of the SHM system,

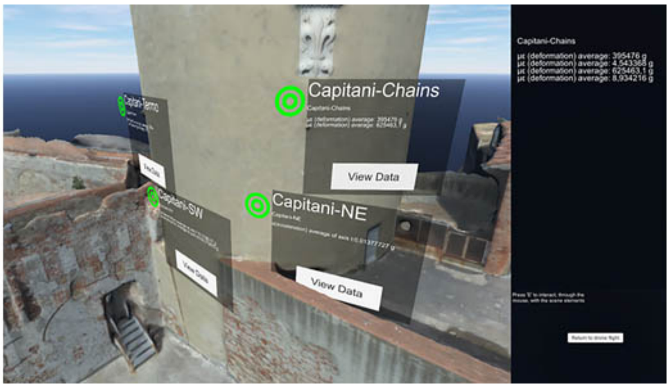


Figure 2.6: The virtual environment of the VR system for the monitoring of historical buildings [Bacco et al., 2020]

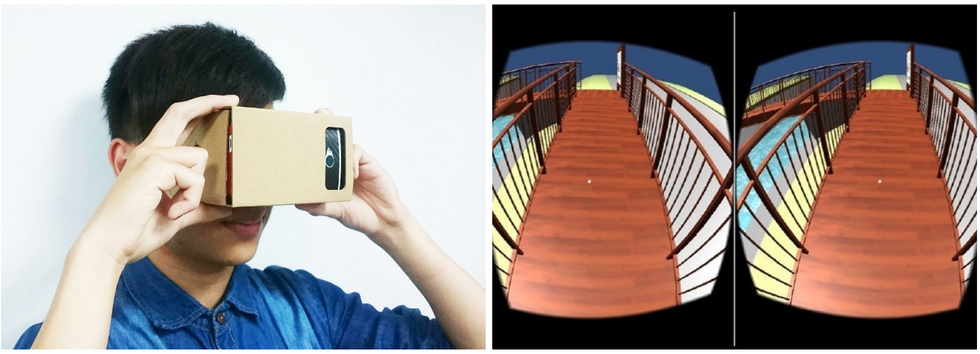
the maintenance of the SHM system, the management of data and metadata and the closure of any activity that exists at that time. Regarding the management of data and metadata, [Napolitano et al., 2018] identified the need for new representations of data in 3D, creating a method that integrates the visualization of the sensors' data inside a virtual environment.

Regarding the integration of VR with the SHM of bridges, [Omer et al., 2018] proposed a workflow for the performance evaluation of bridges using VR. This workflow can be divided into three main categories, in which the last, called post-inspection, is where VR is applied. It starts with the analysis of the data acquired during the inspection, proceeding with the creation of the bridge model and the creation of the virtual environment. Regarding the application of VR technologies in the SHM of cultural heritages, [Bacco et al., 2020] proposed a system that uses VR to help the users in the analysis, inspection, and monitoring of critical structural damage in historical buildings (Figure 2.6). The models of three different historical buildings are created from data acquired by sensor nodes and by one unmanned aerial vehicle.

2.3 Virtual Reality in Dams

In 2002, [Assaf and Hartford, 2002] described British Columbia Hydro Corporation's Life Safety Model (LSM). It was a VR computer system, that used GIS and census data to provide the proper means for dam safety inspectors to simulate, visualize, analyze, and develop plans for dam emergencies. There, users were allowed to generate and analyze dam emergency scenarios.

The architecture of LSM involved several modules. One of them was the People's World Model (PWM), which was included for extracting and integrating data that would be used in the development of static world views, based on which LSM was built. The LSM Scenario Generator was for generating either a single scenario or a set of scenarios for a given time instant. Life Safety Simulator (LSS) was for simulating the impact an inundation caused by a dam fracture would have on the nearby population



(a) A user visualizing the virtual representation of the FRP bridge through the use of the Google Cardboard Oculus

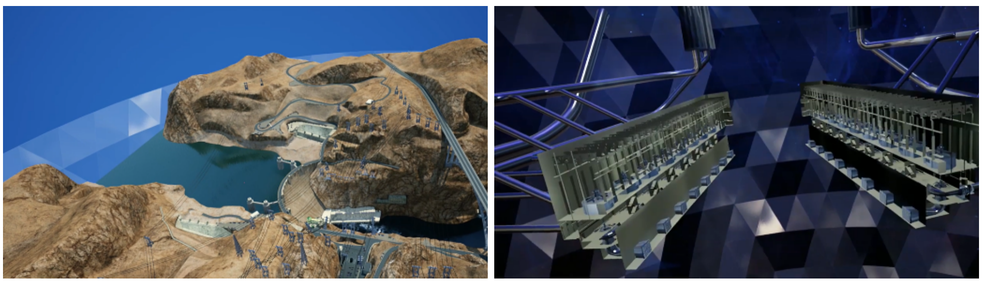
(b) The FRP bridge inside the virtual enviroment

Figure 2.7: The use of the VR system for the visualization of the FRP bridge [Li et al., 2018]

and objects. It also included modules for both scenario management and processing of data input and output, along with the software for visual simulation of the system output.

Besides the capability LSM presented to help in the analysis and assessment of the effects of dam emergencies, it was described as still having a lot to explore and develop in the future. Years later, it was applied in various situations such as, for example, the estimation of the risk of failure of the Brumadinho tailings dam [Lumbroso et al., 2021]. Another example of its application was in the analysis of emergency management interventions, in terms of their life-saving efficiency [Lumbroso and Davison, 2018].

Communicating the risk of failure of dams is imperative, but difficult to be understood by non-specialists through 2D representations. Because of this, [Spero et al., 2022] developed a VR system that represents a case study of the 1976 Teton Dam disaster in a virtual environment. The development of this system used 2D hydraulic model data to create the 3D model of the dam, and image data from an uncrewed airborne system to create the surrounding area. In another work, a VR model representing the



(a) The VR model of the Hoover Dam

(b) The X-Ray Vision representation of the Hoover Dam's engine departments

Figure 2.8: Hoover Dam: IndustrialVR

northern sluice of the ancient dam in Yemen was created by [Kersten, 2007], using digital photogrammetry and laser scanning, to analyze the effectiveness of the evaluation of cultural heritage projects. More than a decade later, [Li et al., 2018] created a computer model of the all-FRP composite pedestrian bridge of Taijiang National Park, along with its surrounding area (Figure 2.7), to perform bridge analysis.

The Hoover Dam, in the United States, is one of the world's most iconic dams and therefore one of the most represented in VR applications. IndustrialVR LLC[3] used an innovative documentary-style approach to develop Hoover Dam: IndustrialVR (Figure 2.8). This is a VR serious game with which users interact using an HTC Vive headset and motion detection controllers, exploring the Hoover Dam and learning about its components, how they work, and what happens inside them. Another example of this is VR Hoover Dam, developed by Anthony F. Arrigo et al.[4], which is a historically based VR serious game, that allows its players to explore the Hoover Dam. There, players can learn about the construction of the Hoover Dam and how it impacted the population, economy, and natural environments.

2.4 Discussion

Here, the different solutions are summarized, compared, and their advantages and disadvantages are discussed. In Table 2.1, relevant features from different solutions are compared, including the type of reality used, their environment, either Interior (Int.) or Exterior (Ext.), if they are integrated with existing BIM, CAD or GIS models, if they are applicable in structural analysis, and if so, what types of structures can be analyzed there.

Regarding the use of VR in AEC, the Workflow of IVR applications, created by [Al-Adhami et al., 2018] was created for performance analysis tasks. However, it is intended for buildings, not including the possibility to analyse the performance of other types of structures, such as dams, and needs the data of the corresponding BIM model. Meanwhile, the application developed by [Hafsia et al., 2018] focused its training on the formwork stabilization task, making it too specific and not flexible for different AEC specialties, such as structural engineering. It also needs to be integrated with a BIM model.

VRIES [Wu et al., 2020] involves the simulation of different scenarios related to construction hazards, making it useful for a high number of construction workers. However, it is too focused on the building construction area, not showing training scenarios for different fields, and needs to be integrated with existing BIM models. Regarding the applications of VR in traffic engineering, the application developed by [Uhr et al., 2019] needs to be integrated with GIS data, for offering an effective 3D visualization of the multidimensional data of roadworks. It also has the disadvantage of being too specific, not being applicable in other fields such as dam engineering.

[3]Hoover Dam: IndustrialVR on Oculus Rift, https://www.oculus.com/experiences/rift/1297777480332012/, December 2021

[4]VR Hoover Dam – A Virtual Reality Game Exploring the History and Construction of an American Icon, https://vrhooverdam.com/, December 2021

Table 2.1: Comparison of different solutions

Solution	Type	Env.	Integration	Str. Analysis	Str. Type
Workflow of IVR applications	VR	Int.	BIM	✓	Buildings
Formwork stabilization training	VR	Int.	BIM	-	-
VRIES	VR	Int.	BIM	-	-
Multidimensional roadworks data visualization	VR	Int.	GIS	-	-
VR model of a hospital	VR	Int.	BIM	-	-
VR-integrated workflow in BIM-based projects	VR	Int.	BIM	-	-
WWGVRSS	VR	Int.	BIM+CAD	-	-
VR Engine	VR	Int.	-	-	-
ImSpector	VR	Int.	Remote sensors	✓	Bridges+Viaducts
Virtual Redlining	AR	Ext.	GIS	-	-
VR system for underground infrastructure inspection	VR	Int.	-	✓	Tunnels
VR workflow for performance evaluation of bridges	VR	Int.	-	✓	Bridges
VR system for the monitoring of historical buildings	VR	Int.	Remote sensors	✓	Buildings
LSM	VR	Int.	GIS	✓	Dams
VR representation of the 1976 Teton Dam disaster	VR	Int.	Remote sensors	✓	Dams
VR model of the Yemen Dam's northern sluice	VR	Int.	CAD	✓	Dams
VR environment with the FRP bridge model	VR	Int.	-	✓	Bridges
Hoover Dam: IndustrialVR	VR	Int.	-	✓	Dams
VR Hoover Dam	VR	Int.	-	✓	Dams

Associated with the BIM and VR integration, the solution proposed by [Tariq et al., 2019], which was a VR model of a hospital, showed having excellent data readability when it comes to decision making. However, it needs to be integrated with an existing BIM model. The VR-integrated workflow in BIM-based projects, presented by [Zaker and Coloma, 2018], also needs to be integrated with BIM, and is not applicable in the field of structural analysis.

Web-Based Game-Like VR Construction Site Simulator (WWGVRSS), developed by [Goulding et al., 2014], needs to be integrated with both existing BIM models and a CAD interface. Additionally, it also has the disadvantage of not being suitable for use in the field of structural engineering. Meanwhile, VR Engine, which was developed by [Wong and Humayoun, 2022], doesn't need to be integrated with any existing model. However, this project was created for the teaching of structural engineering, and not for the performing of structural analysis tasks.

In the field of structural analysis, ImSpector [Veronez et al., 2019] allows the inspection of bridges and viaducts through VR. However, it needs to be integrated with remote sensors, to get the data of the structure that will be analyzed, and does not include the inspection of dams. Meanwhile, the mobile system developed by [Schall et al., 2008], which supports virtual Redlining, is an effective virtualization of the Redlining process. It ensures the possibility of managing complex 3D models in Redlining. However, it uses AR and can only be used on-site, as well as needing to be integrated with GIS data.

The VR system for underground infrastructure inspection, created by [Attard et al., 2018], allows structural analysis inside a virtual environment through the use of VR technology. However, this project was made for the structural analysis of tunnels, not including other types of structures such as dams. The VR workflow for performance evaluation of bridges, created by [Omer et al., 2018], allows the analysis of structure data using VR technology. However, it is focused only on bridges, not including other types of structures.

The VR system for the monitoring of historical buildings, developed by [Bacco et al., 2020], allows the inspection of cultural heritage inside the virtual environment. However, it presents the disadvantage of needing to be integrated with data acquired from remote sensors and doesn't allow the inspection of dams. Meanwhile, British Columbia Hydro Corporation's Life Safety Model (LSM) [Assaf and Hartford, 2002] creates a VR environment for the inspection of dams. This agent-based model has been used in several projects. It has the disadvantage of needing external data, such as GIS and census data, to model the virtual environment.

The VR representation of the 1976 Teton Dam disaster, created by [Spero et al., 2022], can be applied in dam analysis. However, it needs to be integrated with data from remote sensors. The VR model of the northern sluice of the ancient dam in Yemen [Kersten, 2007] allows dam analysis inside a virtual environment. However, it presents the disadvantage of needing to be integrated with existing CAD data. The model of the all-FRP composite pedestrian bridge of Taijiang National Park, created by [Li et al., 2018], used a similar approach, but without the need of being integrated with any existing model. However, it was further away from the spectrum of this work since it was related to the analysis of bridges and not dams.

Hoover Dam: IndustrialVR and VR Hoover Dam are both VR serious games. They allow the users to interactively learn about the Hoover Dam and its components. They are two applications related to dam engineering that don't need any integration, which makes both applications the two projects that are closer to this work. However, none of those two applications were used for this work since they were proprietary software, so there was no access to them. They were also VR serious games for teaching about the dam, and not applications for dam health monitoring, which was the focus of this work.

3

VRCabrilAnalysis

Contents

In this chapter, the requirements analysis and development of a VR prototype called VRCabrilAnalysis, are described, as well as its concept and architecture. This prototype, developed as a proof of concept, has as its main objective contributing to the development of VR applications within the scope of dam safety control, continuing to be developed in future projects. It also has the goal of gathering information concerning the utility and efficiency of applying VR in the SHM of dams, by evaluating it with real users. VRCabrilAnalysis has dam managers and engineers as target users.

3.1 Requirements Analysis

To be possible to carry out the development of VRCabrilAnalysis, it was essential to know the requirements of LNEC and to understand the tasks that correspond to those requirements. This was done through meetings with LNEC staff, to raise and analyze the requirements, and to explain how the dam health monitoring tasks were performed. These meetings also served to determine the necessary data concerning the Cabril dam to be included and visualized in the prototype.

It was crucial to understand the expectations that dam engineers would have regarding a VR system designed for dam health monitoring tasks. The requirements for the development of this prototype included the incorporation of features that the target users would expect to be in the system. Those features were decided during the meetings with the LNEC staff.

Dam experts from LNEC provided material that was necessary for the development of the prototype. This included various point clouds of the Cabril dam, obtained from laser scans, and a texture for the dam downstream's face, which was a Portable Network Graphics (PNG) file created from an orthorectification of photos taken at the Cabril dam. The requirements for the development of the prototype also considered the available materials.

Information about the sensors was provided by LNEC. This included the different types of sensors that were present in the Cabril dam, their identification, and their position, which was both their block and elevation. Representing the different types of sensors in the virtual environment ended up being a requirement for the development of VRCabrilAnalysis.

The target users had been using the same processes and methodologies over the years to perform the dam health monitoring tasks. Because of this, it was important to have the technology integrated smoothly into the existing workflow. In Table 3.1, the requirements that were defined for the development of VRCabrilAnalysis are shown, as well as their priority, difficulty of implementation, and if they were or were not implemented. The requirements that could not be implemented were left for future work.

Table 3.1: Raised VRCabrilAnalysis requirements

Name	Priority	Difficulty	Implemented
Coherent representation of the Cabril dam	High	High	✓
Representation of the environment in VR	High	High	✓
Collaborative application	High	High	
Controller-based locomotion	High	Medium	✓
Teleportation-based locomotion	Medium	High	✓
Collision detection	Medium	Medium	✓
Movement boundaries	High	Low	✓
Display and selection of anomalies	Medium	High	
Sensor selection through Raycasting	High	Medium	✓
Representation of the geodetic marks	High	Low	✓
Representation of the plumblines	High	Medium	✓
Representation of the GNSS antenna	High	Low	✓
Representation of the water elevation sensor	Low	Low	✓
Representation of the leveling marks	Medium	Low	✓
Representation of the accelerometers	Medium	Medium	✓
Highlights in the sensors depending on their data	Low	High	✓
Display information about the selected sensor	Medium	Medium	✓
Option to select a certain earthquake	Low	Medium	
Option to display additional data	Low	Low	✓
Display graphs containing the evolution of sensor registered data	High	High	✓
Real-time data update	High	High	
Possibility to increase and decrease data granularity	High	High	✓
Graphs panning feature	High	Low	✓
Brush feature to display the data from a chosen time interval	Medium	Medium	✓
Display the values of a certain record in a tooltip	Medium	Low	✓
Selection of the data attributes to be represented in the graph	Medium	Medium	✓
Move the informative tables	Medium	High	✓
Scale the informative tables	Low	Medium	✓
Option to see the visual evolution of the dam over the years	Medium	High	
Possibility to write notes in the virtual environment	High	High	
Feature for capturing and sharing in the virtual environment what is being seen	Medium	Medium	

3.2 Approach Overview

VRCabrilAnalysis is a VR prototype for the immersive analysis of sensor data from the Cabril dam. The user can move around the virtual environment through either controller-based locomotion [Boletsis and Chasanidou, 2022] or teleportation-based locomotion, by using the VR controllers. The prototype contains different sensors that the user can select and interact with. After selecting a certain sensor, the user can read information about it, see the last measured values, or plot the evolution of its data over time. The user can select one of these options by using the interactive menu, that appears after one of the sensors was selected. The user can choose a certain portion of the data to analyze, by using different techniques of data visualization, and can move and scale the informative tables.

3.2.1 Concept

VRCabrilAnalysis was developed in Unity[5], a graphical engine that allows its users to develop interactive programs. Unity is arguably the most popular platform for the development of VR applications, due to its

[5] Unity, https://unity.com/

accessible interface, as well as its ability to compile projects for a large variety of VR hardware (such as Oculus Rift or HTC Vive, for example), and the versatility of the C# language (its main language) [ISAR, 2018].

The development of VRCabrilAnalysis started with the creation in Unity of a 3D first-person game prototype, before converting it to a VR application. This application allows to visualize the environment and move around it thanks to the Unity Input Actions system and select a certain sensor through Ray-casting. The dam was modeled in Meshlab [Cignoni et al., 2008] and using Python scripts, while its surrounding area was modeled in Blender and the sensors were modeled in either Blender, Meshlab, or Unity. The prototype has object collision enabled and gravity disabled, as the users can stay still inside the application, regardless of their position, but can't move through either the boundaries or objects in the virtual environment.

VRCabrilAnalysis was specific to the Cabril dam and not generalized to other dams, due to the complexity of correctly representing a dam in a 3D model. In addition, the sensors installed in a particular dam are too specific to that dam, further limiting their applicability to other dams.

3.2.2 Architecture

The architecture of VRCabrilAnalysis (Figure 3.1) followed the Model-View-Controller (MVC) pattern [Sommerville, 2015], which contained the Model, the View, and the Controller components. The Model was represented by the components related to the Cabril dam such as its model and its data, as well as its sensors and surrounding area. The interaction parameters, the information about the state of the plotted data, and which and how the informative tables were displayed, also represented the Model. The Model flowed information to the modules corresponding to the View and the Controller components.

The Interface Module represented the Controller. It contained the necessary means for the user to

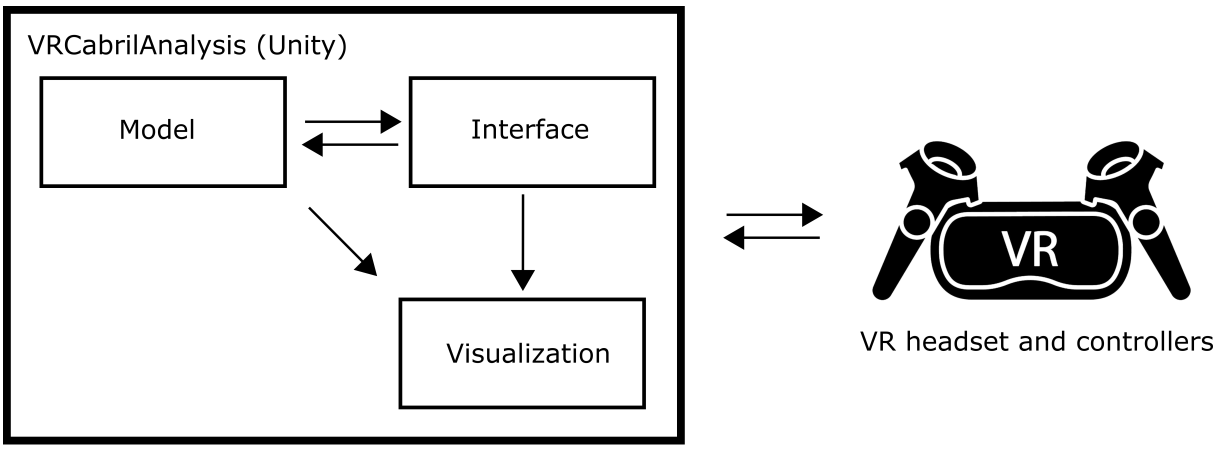


Figure 3.1: System Architecture

be able to interact with the system and updated the Visualization Module. The Visualization Module represented the View and rendered the scene with the information received from the Model. The application communicates with the VR equipment, with the View component displaying the scene in the VR headset, while the VR headset tracks the head movement, sending the head movement data to the application. The VR controllers send data about the user interaction to the application.

3.3 Model

The model of the Cabril dam consisted of different game objects, which were the dam structure, the road, the hydropower plant, and the intake tower. Each game object contained one or more meshes inside containing its respective material. The mesh from the downstream face was created by editing a Polygon File Format (PLY) file gathered from laser scans performed by LNEC at the Cabril dam, with the vertices equivalent to the downstream face. Then, a Python script was created, for sampling this original point cloud and generating its triangles in Meshlab, by using the Ball-Pivoting Surface Reconstruction filter [Bernardini et al., 1999]. The remaining meshes were created manually. The materials present in the meshes either contained a certain texture (with the respective mesh having its UV coordinates computed) or a grey opaque material (in the case of the upstream face).

The surrounding area consisted of three different terrain meshes, with the corresponding textures having different levels of detail. Each terrain mesh was created in Blender and converted to a Terrain object with the Unity Terrain Tools[6]. One of the terrain meshes represents the surrounding area inside the user's boundaries, the other represents the surrounding area outside of it and the last one represents the limit between the inside and the outside of the boundaries, to avoid an evident difference between the other two meshes.

3.3.1 Model of the Dam

A coherent representation of the Cabril dam was needed to provide the users with an increased feeling of presence [Mandal, 2013]. For this, several approaches were made, using data that was acquired and processed by LNEC engineers. Initially, access to the raw data from the dam was not available, leading to the creation of a preliminary model of the dam before any contact with the information provided by LNEC. This preliminary model was a theoretical representation based on structural models, resulting in a PLY file containing 477 vertices and 761 faces.

The development of the project started by importing the preliminary model to Unity, before starting to create the first version of the surrounding area. As that model was generated through theoretical

[6] Terrain Tools | Terrain | Unity Asset Store, https://assetstore.unity.com/packages/tools/terrain/terrain-tools-64852, March 2022

operations rather than actual data analysis from the Cabril dam, it was only used before obtaining the raw data from LNEC, as that model would present an incorrect representation of the dam.

The data from LNEC contained the dam model, several PLY files with information gathered from different laser scans of the downstream face of the dam, and photos. Due to the lack of access to appropriate software, it wasn't possible to use the LNEC model. Because of this, it was mandatory to create a new model by using the received PLY files, as well as the photos of the dam, to create a coherent representation of the Cabril dam. By analyzing the size of some binary files, it was concluded that the LNEC model only contained vertices and triangles, as their respective files were the only ones that had a size higher than zero.

The development of the dam model started by creating the mesh, using Meshlab to flatten several PLY files from the received folder into a single new point cloud. Since the used PLY files were obtained from laser scans taken from different distances and orientations, this approach resulted in an inconsistent point cloud. It was later concluded that each PLY file contained enough vertices to coherently represent the dam, and so it was decided to choose one of the files, containing 103K vertices, to create the model.

Several approaches were followed to create the faces of the mesh, using Meshlab most of the time. First, Meshlab was used to compute the normals of the point cloud and then generate a Screened Poisson Surface Reconstruction [Kazhdan and Hoppe, 2013]. This algorithm generated more faces on the top and on the front of the point cloud, which were directly removed in Meshlab. However, the resulting mesh presented noise, so other approaches were tried.

It was tried to construct the mesh using other Meshlab algorithms for Surface Reconstruction, but the resulting mesh always presented a circular ripple in the center, and because of this a C# script was created to run in Unity. That script read the vertices of a certain PLY file and generated a mesh. One of the PLY files was selected, containing 189K vertices, to be used in the script since it was thought that it had the vertices ordered by a Delaunay triangulation [Lee and Schachter, 1980].

With that file, it was just needed to iteratively choose the next three vertices of the point cloud to create each triangle. However, the resulting mesh presented triangles with vertices at the two ends of the dam. For this, it was added a condition to only create triangles whose vertices had a distance from each other below a certain threshold, but the resulting mesh was unrealistic, with both overlapping triangles and parts of the mesh with triangles missing. The other issue with this script was that it only generated the mesh when the program was running, so it was harder to place the mesh in the scene than having it already as a Filmbox (FBX) file. Having no success with this approach, the same file was opened in Meshlab to apply the Voronoi Filtering [Amenta and Bern, 1998], but the software always failed to compute it in that point cloud.

On Meshlab two text files from the LNEC data were opened. One of them, with 258K vertices and

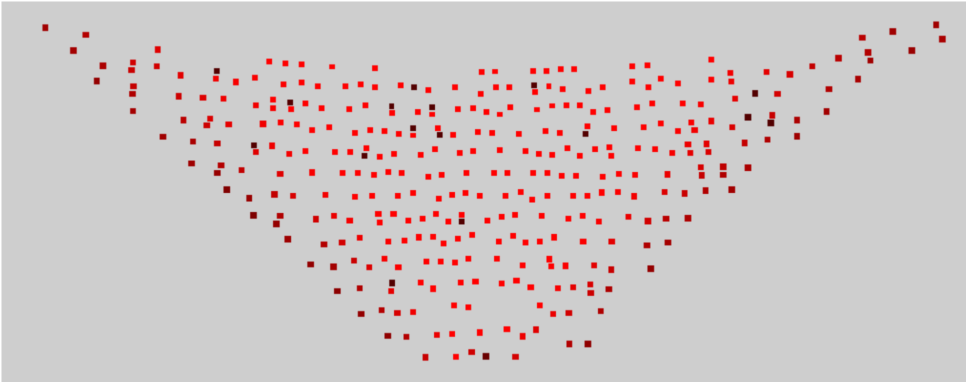


Figure 3.2: The treated point cloud, with 340 vertices, representing the downstream face of the dam

516K faces, had a mesh that didn't represent the dam. The second one contained 259K vertices and 516K faces and represented the downstream face of the dam. This second file was manually converted to a file in the Object File Format (OFF) format, and various Meshlab's remeshing, simplification, and reconstruction filters were tried in it, but the resulting mesh still presented a circular ripple in the center.

After those failed approaches, the next approach was based on the method used by [Baptista, 2016], which had the Cabril dam represented as a point cloud consisting only of vertices and their respective colors. For this, one of the PLY files was utilized, containing 103K vertices. To be able to import this type of file to Unity, a package from GitHub was used for importing PLY files to Unity[7]. However, this approach was only useful with an extremely large amount of vertices, as a much lower number of vertices would not be able to show a realistic representation. Because of that, the gathered point clouds couldn't provide a realistic representation of the Cabril dam.

Since that approach was unsuccessful, the dam was again represented by a mesh, this time to add a texture to it. For this, a new PLY file was created, by removing some vertices from a previously created

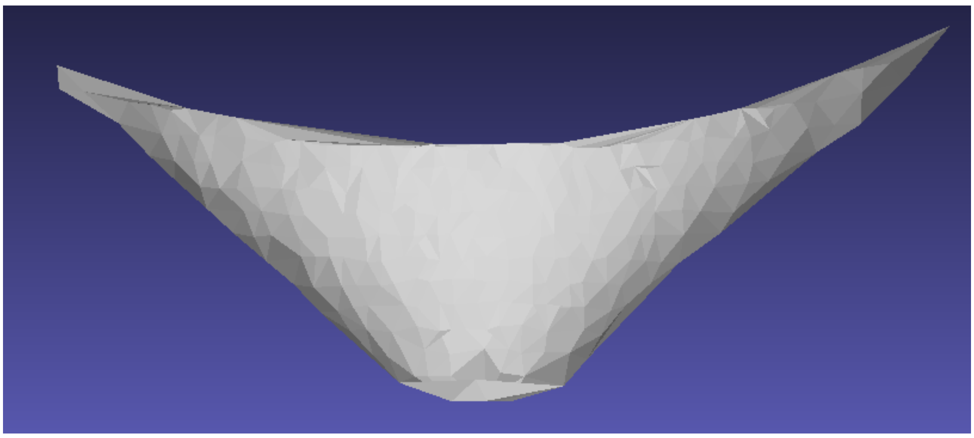


Figure 3.3: The mesh of the downstream face of the dam, containing 340 vertices and 598 faces

[7]jorge-sepulveda/Pcx: Point cloud importer & renderer for Unity, https://github.com/jorge-sepulveda/Pcx, April 2022

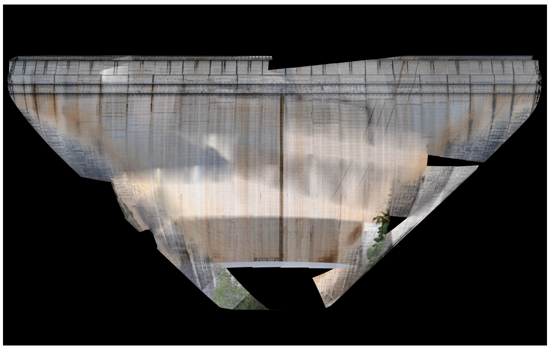


Figure 3.4: The texture used for the mesh

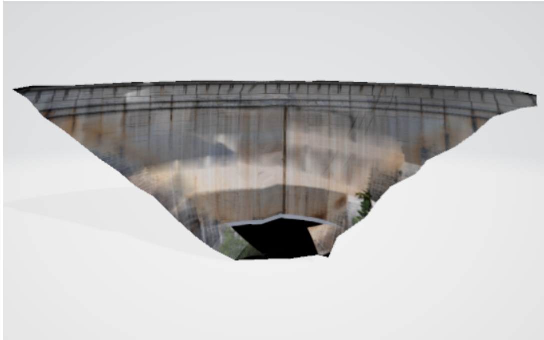


Figure 3.5: The mesh with the texture attached

PLY file (with 103K vertices) in Meshlab, to contain only the vertices corresponding to the downstream face of the dam. This new PLY file ended up having 79K vertices.

To create a mesh from this point cloud, Meshlab's remeshing, simplification, and reconstruction filters were once again explored, with the Ball-Pivoting Surface Reconstruction filter [Bernardini et al., 1999] being the one that was decided to be used. However, this resulted in an extremely irregular mesh with numerous overlapping triangles. To resolve this issue, a Python script was created to generate a sample of the previous point cloud with only vertices at specific elevations with a maximum horizontal distance of five meters from each other. The sampled point cloud was then saved to a new PLY file, that ended up containing 340 vertices. This was the final approach for the creation of the point cloud that represented the dam downstream's face, and the resulting point cloud is represented in Figure 3.2.

Meshlab's Ball-Pivoting Surface Reconstruction filter [Bernardini et al., 1999] was applied once again on that new file, generating a mesh that realistically represented the dam. After applying the filter, the faces of the vertices that were unconnected were manually added. This approach resulted in a PLY file with 340 vertices and 598 faces, whose mesh is represented in Figure 3.3. After that, it was needed to correctly map the UV coordinates of the texture, which was a PNG file from LNEC (Figure 3.4), to the vertices of the mesh.

For that, a Python script was created. For each iteratively traversed vertex of the mesh, this script computed a linear interpolation for their respective U and V values, based on their X and Y values with the values of a maximum and minimum extreme in both the mesh and the texture. After defining the UV mapping of each vertex, the script writes the mesh with the UV coordinates in a new Object File (OBJ). This resulting OBJ file, with 340 vertices and 598 faces (each one with the corresponding UV coordinates), was the final mesh that was created to correctly represent the downstream face of the dam in the scene. A material with an opaque rendering mode, containing the texture, was applied to the mesh in Unity, as shown in Figure 3.5.

The upstream face of the dam contained the same mesh that was used for the downstream face. It also contained a grey opaque material. In the scene, a game object was created containing both the

Figure 3.6: The model of the dam in the scene

downstream and the upstream faces of the dam. This game object was exported to an FBX file to be possible to create the road on top of the dam, by importing the file to Meshlab and exporting it to a new PLY file, which was manually edited by removing the original triangles and creating new triangles that united the vertices in the top of downstream and the upstream faces. The mesh of the road ended up having 41 faces.

To assign a texture to the road, it was created a script similar to the one used to do the UV mapping of the downstream face, which read the original PLY file and created a new OBJ file with the UV coordinates mapped in the file. This texture was a screenshot taken from Google Maps[8] with a satellite view of the top of the Cabril dam.

The hydropower plant consisted of four different cubes created in Unity and exported from Unity to FBX files, to be imported to Meshlab and then exported to OBJ files. Their UV mapping was done manually by editing the OBJ file, as each cube contained a low number of vertices and triangles. The texture was created with different photos of the Cabril dam, taken from a website called Mapio[9].

The intake tower consisted of two cube objects created in Unity and exported to FBX files, which were therefore imported to Meshlab and exported to OBJ files, where their UV coordinates were manually written to apply their texture. Half of the texture contained the top of the intake tower (taken from a Google Maps screenshot of a satellite view of the Cabril dam) and the other half contained its side faces (taken from Mapio). The final representation of the Cabril dam in the virtual environment can be seen in Figure 3.6.

[8]Google Maps, https://maps.google.com/
[9]Pedrógão Grande - Barragem do Cabril | Mapio.net, https://mapio.net/pic/p-9060740/, August 2022

3.3.2 Model of the Surrounding Area

To create the surrounding area of VRCabrilAnalysis, a software called Blender[10] was used. The creation of the surrounding area started with the creation of a Basemap using satellite data from Google and elevation data from the server *marine-geo.org GMRT*[11]. The resulting mesh was exported and then imported to Unity. Since Blender couldn't export the texture of the created Basemap, the mesh was edited in Unity using the Terrain tools from Unity Asset Store, to make it as coherent with the surrounding area of the Cabril dam as possible.

However, without a texture, it was not possible to have an area matching the surrounding area of the Cabril dam. To solve this, it was necessary to generate a mesh with a texture representing the Cabril area. For this, another software called SketchUp[12] was used, and a new geo-location was added, by selecting the region around the Cabril dam with a zoom level of 16. With the Geo-Location added to the SketchUp project, a plugin was downloaded from SketchUcation[13], to be possible to add a thickness to the map, turning it into a solid, instead of a face.

SketchUp generated a texture in a separate file when the mesh was exported. However, the texture's resolution did not fulfill the minimum requirements to reach a coherent representation of the surrounding area. The resulting mesh also presented heights inconsistent with the dam's surrounding area with, for example, the sea having bumps instead of being flat.

Because of this, a new texture was manually created, by using the satellite view in Google Maps, taking 45 screenshots in different zones of the map. The screenshots were loaded in the panorama editor Hugin[14] and the orthographic lens type was chosen to merge all the screenshots into a single image. In Blender, a new Basemap was generated, with corresponding elevation data, which mesh was then exported and imported to Unity. Then was applied the texture that was created and the Terrain tools were used to lower the part of the terrain that contained the dam, to add the model of the dam on it. This terrain mesh represents the area inside the user's boundaries.

A Level of Detail (LOD) approach [Heok and Daman, 2004] was used to represent the surrounding area. To make the horizon more realistic, a Skybox from an asset downloaded from Unity Asset Store[15] was added. An additional Basemap with corresponding elevation data was also created, covering an area around 204 times larger than the Cabril mesh already present in Unity. To create its texture, 70 screenshots were taken from Google Maps with a satellite view and then loaded in Hugin, with the orthographic lens type to merge them into the texture image. This second terrain mesh represents the area outside the user's boundaries.

[10] Blender, https://www.blender.org/
[11] *marine-geo.org GMRT*, https://www.marine-geo.org/index.php
[12] Sketchup, https://www.sketchup.com/
[13] Joint Push Pull Interactive | SketchUcation, https://sketchucation.com/plugin/715-jointpushpull, April 2022
[14] Hugin, https://hugin.sourceforge.io/
[15] Classic Skybox | 2D Sky | Unity Asset Store, https://assetstore.unity.com/packages/2d/textures-materials/sky/classic-skybox-24923, July 2022

To avoid a very evident difference between the quality of the texture inside the boundaries box and the quality of the texture outside of it, a third Basemap was created in Blender, also with corresponding elevation data, with an area slightly larger than the area of the mesh inside the boundaries box. For the texture of this third terrain mesh, 20 screenshots were taken from Google Maps with a satellite view, with them also being loaded in Hugin with the Orthographic lens type selected.

To make the surrounding area more realistic, tree prefabs were added to the terrain through the paint trees feature of the Terrain tools. The brush from that feature was used to paint the trees in the terrain parts corresponding to the parts of the Google Maps area where trees were present. A single prefab was used for all the placed trees, and the tree density and tree height of the brush were altered based on the distribution of trees in different parts of the area shown on Google Maps.

While developing the prototype, a problem was faced, where the trees turned from 2D billboards to 3D when moving through them, and then shifted back to 2D when moving away from them. That happened because, to improve performance, the trees from the terrain are rendered as 2D billboards when they are at a given distance from the camera. To fix this, the fade length option and the billboard start option were increased. The new values of these two options provided both realism, as the distance from the camera in which trees turned into billboards was higher than the maximum distance it could have due to the boundaries, and good performance.

The properties of the center eye anchor were changed to ensure a stable representation of the surrounding area inside the virtual environment. The center eye anchor ended up being a physical camera with a Field of View (FOV) of 140, which ensures the rendering of the tree prefabs on the necessary area, such that the user doesn't see any tree prefabs switching from visible to not visible, and also ensures a focal length enough to see the terrain with an acceptable level of detail.

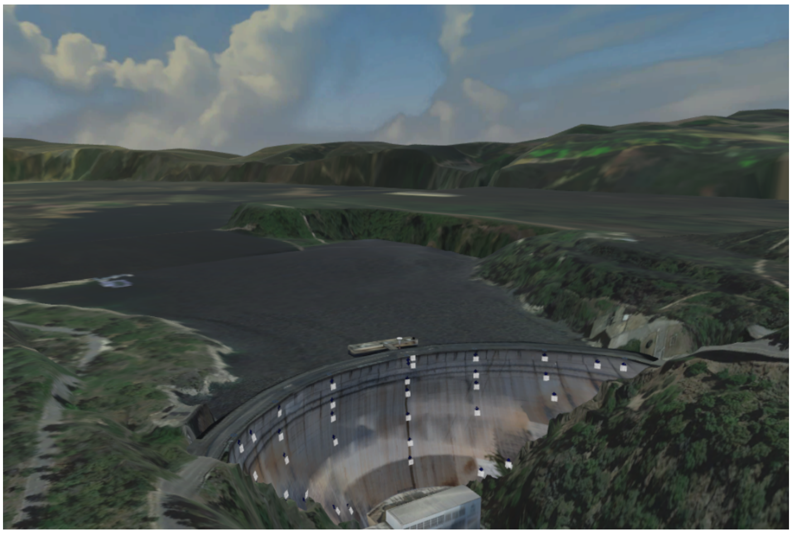


Figure 3.7: The surrounding area of VRCabrilAnalysis

The tree prefabs ended up being removed from the scene, to achieve a better performance, as having the trees in the scene made the visualization of the prototype appear blurry and shaky after opening the data charts, as a result of TimeWarp[16], which is a mechanism that Oculus Rift uses to interpolate intermediate frames, to achieve a target frame rate in cases when the prototype does not reach the sufficient value of Frames per Second (FPS). The final representation of the surrounding area is shown by Figure 3.7.

3.4 User Interface

In VRCabrilAnalysis, the user can use the controllers to move around and select different sensors through Raycast. The sensors become highlighted when the user points to them, and if one of them is selected, an interactive table appears, displaying information about the selected sensor. With the interactive menu, the user can plot the data about the values measured by the sensor, expand the information about it and open a table containing instructions on how to interact with the prototype.

The evolution of data is represented in 2D line charts, integrated with the virtual environment, with which the user can interact, with features such as the brush for selecting a certain interval of data, zooming in and out, and the pan feature. Both the line charts and the table with the instructions can be scaled up and down and moved such that the user can visualize and interact with them as effectively as possible.

3.4.1 Representation of the Sensors

The representation of the sensors was initially based on their adopted 3D symbology in DamAR [Verdelho Trindade et al., 2019]. For this, in the prototype, the geodetic marks were represented as a cylinder created in Unity with a cone created in Blender on top. Both plumbline types, weighted and inverted, consisted of a cylinder created in Unity, two cones created in Blender for the coordinometer base with another cone created in Blender on the bottom, and an edited cube on top, created in Meshlab. The Global Navigation Satellite System (GNSS) antenna (used for measuring displacements) consisted of a circumference created in Blender, with a symbol in the middle, that was a cone created in Blender with a semi-sphere on top created in Unity and edited in Meshlab. The geodetic marks were represented in blue, the plumblines were represented in red and the GNSS equipment was represented in green.

Since realism is one of the objectives of VR, this representation, despite working well in AR, would not be the ideal one, as the virtual environment would not match the on-site visualization of the Cabril dam. For this, the sensors needed to have a representation as similar as possible to the sensors physically

[16] Asynchronous TimeWarp (ATW) | Oculus Developers, https://developer.oculus.com/documentation/native/android/mobile-timewarp-overview/, October 2022

Figure 3.8: From left to right: The representation of the geodetic marks, the plumblines, and the GNSS equipment

present in the dam. Their final representation is shown in Figure 3.8.

The geodetic marks ended up being represented as a plane created in Unity, with a blue target symbol as its texture. This texture was a vectorial image created in Inkscape. The material containing that texture had a cutout rendering mode, which is a rendering mode that allows the creation of a transparent effect with hard edges between the opaque and transparent areas. It also had a blue Albedo and a second Albedo color map, which are the parameters that control the base color of the surface.

In their second representation, the inverted plumblines consisted of their wire, represented with a thin cylinder with a realistic steel material from an asset from Unity Asset Store[17]. Their coordinometer bases, which are instruments that measure the structure's radial and tangential displacements, were represented with a cube and a cylinder. The weighted plumblines consisted of the two different components from the inverted plumblines plus one top support, represented by three blue cubes, and a steel weight at the bottom end, represented by a cube with the steel material. All the meshes present in the

(a) Water elevation sensor **(b)** Leveling mark

Figure 3.9: The representations of the water elevation sensor and the leveling marks

[17] Real Materials Vol.0 [FREE] | 2D Textures & Materials | Unity Asset Store, https://assetstore.unity.com/packages/2d/textures-materials/real-materials-vol-0-free-115597, June 2022

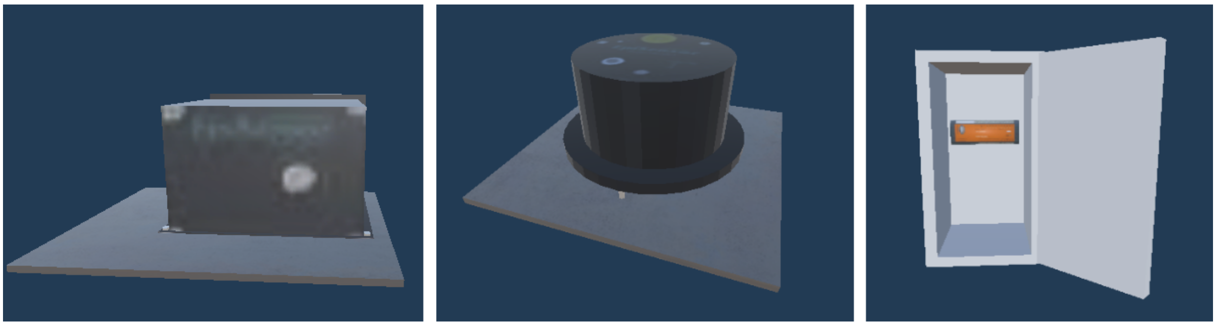


Figure 3.10: From left to right: The representation of the uniaxial accelerometers, the triaxial accelerometers, and the data acquisition units

plumblines were created in Unity.

The representation of the plumblines was changed after the preliminary evaluation, as that representation would not make the coordinometer bases recognizable inside the virtual environment. Because of this, the representation of both plumbline types returned to their previous representation (based on DamAR), with the realistic steel material from the wires having a red albedo color, and the coordinometer bases consisting of two cones with the same material as the wire.

The prefab representing the GNSS equipment consisted of several meshes, all created in Blender. The GNSS station antenna was represented by two meshes, one with a white material and the other with a green material. The column supporting the antenna consisted of two cylinders built from Non-uniform rational B-spline (NURBS) surfaces with a metallic material. The stainless steel tube was represented by a cylindrical mesh, with a metallic material, and the screw thread was represented by a NURBS surface cylinder, with a black material. The coaxial cable that connects to the antenna was represented by various cylindrical meshes, with a black material.

The column and the mounting bracket dimensions in the scene were equivalent to their real dimensions, present in [Morais, 2017], while the GNSS antenna had a higher dimension than in reality, as it was the main focus of the GNSS equipment in the prototype. One water elevation sensor was also represented in the prototype. It consisted of six cylindrical meshes created in Blender, all with the same material as the screw thread from the GNSS antenna. This representation can be seen in Figure 3.9(a).

After creating and modifying those sensors, the leveling marks were created, which were initially represented the same way as the geodetic marks, but with a quarter of their scale. This representation of the leveling marks was changed after the Preliminary Evaluation, as it didn't match the aspect of the leveling marks in real life. Their new representation consisted of two cylinders created in Blender, with realistic steel material, and can be seen in Figure 3.9(b).

The different types of accelerometers were also created, namely the uniaxial accelerometers and the triaxial accelerometers, as well as their data acquisition units [Oliveira and Silvestre, 2017], being their representation shown in Figure 3.10. All the meshes present in the accelerometers were created

(a) The dam downstream's face before pointing to it **(b)** The dam downstream's face after pointing to it

Figure 3.11: The interaction between the Raycast and the dam downstream's face

in Blender, with the meshes that required to do a UV mapping being exported as an OBJ file and the remaining ones being exported as an FBX file.

Both accelerometers had a cube with the steel material representing their base, with four cylinders with the aluminum material from the same asset representing the screws attaching the accelerometer to the base. The uniaxial accelerometer was represented by one main cube with thinner cubes behind and at the bottom, while the triaxial accelerometer was represented by one main cylinder with a shorter cylinder at the bottom. Both accelerometer meshes were exported as OBJ files, to be possible to do the UV mapping and therefore apply their texture in Unity. The data acquisition units were represented as a cubic mesh, exported to an OBJ file, with the UV mapping for its specific texture. The mesh for each data acquisition unit was inside another mesh, representing a cubic box.

Because the plumblines and the accelerometers are situated inside the dam, it would be impossible for the user to see and interact with those two types of sensors. Because of this, the material of the dam downstream's face changes from its original material (Figure 3.11(a)) to a new material (Figure 3.11(b)), with a transparent rendering mode, when one of the controllers points to the dam downstream's face,

(a) An uniaxial accelerometer with a green highlight **(b)** A geodetic mark with a red highlight

Figure 3.12: The highlights that appear when pointing to the sensors

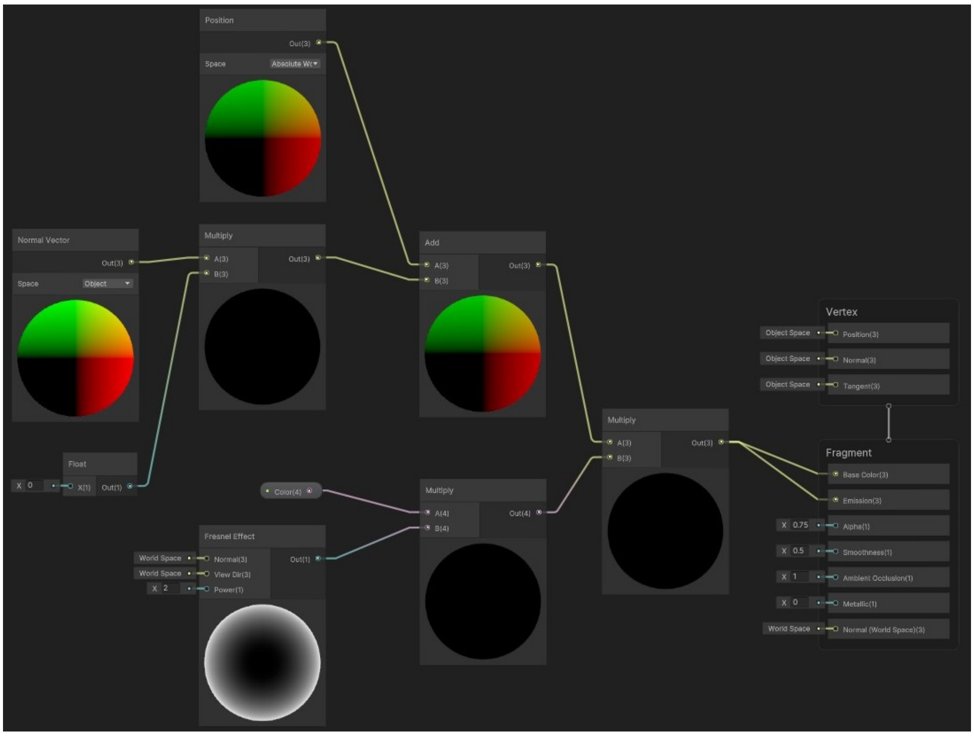


Figure 3.13: The highlight shader graph

with its mesh becoming without any collider when this interaction happens. This allows the user to see and interact with the sensors inside the dam. The material of the dam downstream's face after pointing to it was changed after the Preliminary Evaluation, with the new material containing the downstream face texture with its albedo alpha value changed to have a certain level of transparency.

The sensors are also highlighted (Figure 3.12) when one of the controllers points to them, which makes the user understand when he is interacting with a sensor and makes the plumblines and accelerometers more visible behind the transparent material. An interacted sensor is highlighted with a green color (Figure 3.12(a)) when it has a data file attached to it (which consequently allows the user to see its data evolution in time and its last recorded values) and is highlighted with a red color (Figure 3.12(b)) when its data file doesn't exist.

Both highlight materials were created from a lit shader graph from the built-in render pipeline (which is the project's render pipeline). This shader graph built a lit material that allowed material override and had a transparent surface type, an alpha blending mode, a G Equal (Greater or Equal) depth test and it was rendered in both faces of the sensor, with the Fragment Normal Space using the World Space. The project uses the default Built-in Render Pipeline instead of the universal render pipeline because the tree prefabs placed in the surrounding area would not work with their materials corresponding to the universal render pipeline.

The created shader graph is represented in Figure 3.13. It contained a color variable (that was different for each one of the two materials) multiplied with a fresnel effect, to add a glowing effect to the highlight. The vector resulting from this multiplication was then multiplied with the vector resulting from the position in absolute world space added to the normal vector in object space. The output of this multiplication was used for the base color and the emission of the fragment. To share the highlight between both eyes, this project used a multi-pass stereo rendering mode, which results in the scene graph being traversed twice, leading to one eye being rendered at a time.

Each sensor in the scene has attached a mesh collider, to allow the user to select it with Raycasting, and a C# script, that stores information about its sensor and reads the Comma-Separated Values (CSV) file with its recorded values if it exists. When a user points to a certain sensor, this script adds the corresponding highlight material to each mesh that the sensor contains. In case the user clicks on the sensor, an interactive menu appears, allowing the user to select the desired option.

3.4.2 Interactive Menu

The content in the interactive menu depends on the selected sensor, as it displays information about it, such as its name and its type, as well as the coordinometer base position and its plumbline type (in case the selected sensor belongs to a plumbline) or the accelerometer type (in case the selected sensor is an accelerometer). It also contains three selectable labels, one that plots the time evolution of the sensor data, one that displays additional information about the sensor, and the other that displays a table explaining what every key from the controllers does.

The additional information, displayed by clicking in the middle selectable label, shows information about the types of physical quantities that the selected sensor measures, the last recorded value for each one of those quantities, and the date and hour when those last values were registered. In case the selected sensor is an accelerometer, the additional information includes the date and epicenter of the earthquake measured by that accelerometer, instead of the last recorded values and their date.

Figure 3.14: The interactive menu of VRCabrilAnalysis

Initially, to avoid blocking the least possible portion of the visualization, the menu consisted of different cubes, depending on the sensor type. Each cube was for the sensor name, the sensor type, the coordinometer base position, and the different options. When the option for showing additional information was selected, three new cubes were displayed, one for each information content.

The interactive menu would not be intuitive with this representation, with selectable and non-selectable elements not being distinguishable, so a different approach was followed, with the menu being a Unity UI Canvas. This representation had the options represented as selectable labels, which were created as Unity UI Images, each one with a cubic mesh as its child to detect the user interaction with Raycasting. With this representation, the option for displaying more information worked by expanding the menu, with the additional information being shown under the selectable labels. In addition to being more intuitive, this representation also ended up blocking a smaller portion of the visualization than the initial representation. The icons of the selectable labels were 2D sprites downloaded from Flaticon[18], and the border of both the menu and the selectable labels was a 2D sprite obtained from a GitHub repository[19].

Initially, after selecting a certain sensor, the menu appeared on top of the controller that was used to select that sensor. The position of the menu was changed after the preliminary evaluation, with the new position of the menu being in the middle of the HMD FOV. This was done because the previous approach reduced the ease of interacting with the menu, being only possible to select a certain option with the controller that was opposite to the one that was used to select the sensor, and also made the menu more visible for the user than with the previous approach. The final representation of the menu can be seen in Figure 3.14.

The menu disappears when the option for plotting the time evolution of data is selected, to allow the user to visualize the entirety of the table. The user can toggle between the menu being visible or

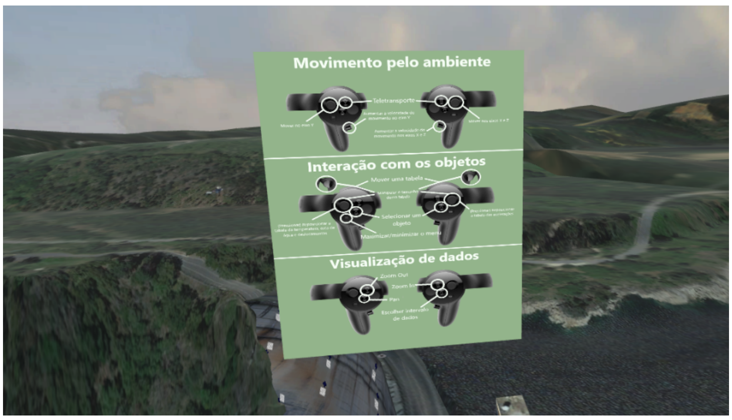


Figure 3.15: The table with the instructions about what the button of each controller does

[18]Flaticon, https://www.flaticon.com/, June 2022
[19]Fist-Full-of-Shrimp/Unity-VR-Basics-2022: Unity VR Basics 2022, https://github.com/Fist-Full-of-Shrimp/Unity-VR-Basics-2022, August 2022

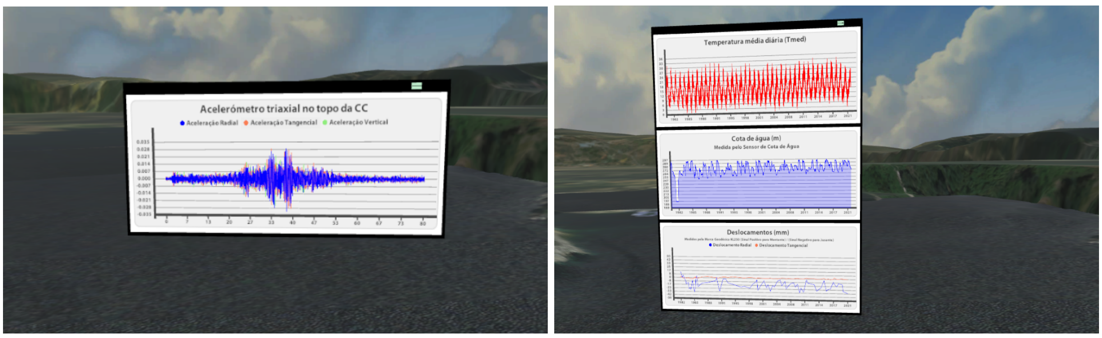
invisible by clicking on the menu button, present in the left controller. To toggle between the data charts being visible or invisible, the user can click on the left selectable label of the menu, as well as the right selectable label of the menu if he wants to toggle between the instructions table being visible or invisible. The instructions table (Figure 3.15) is a Unity UI Canvas that contains a cubic mesh as its child, to be possible to detect the user interaction through Raycast, and a Unity UI Image containing an image of the instructions about what every key from both controllers does.

3.4.3 Data Visualization

The displayed data depends on the selected sensor. In case the selected sensor is an accelerometer (Figure 3.16(a)), the table that is displayed contains one line chart representing the evolution of the accelerations during a specific earthquake. This line chart either contains just the radial acceleration (in case the selected accelerometer is uniaxial) or contains the radial, tangential, and vertical accelerations (in case the selected accelerometer is triaxial).

If the selected sensor is other than an accelerometer (Figure 3.16(b)), the table displayed contains three line charts, one at the top showing the evolution of the temperature (which data is present in a separated CSV file), one at the middle showing the evolution of the water elevation and one at the bottom showing the evolution of the displacements. This last line chart can either contain just the radial displacements (in case the selected sensor is a leveling mark), the radial and tangential displacements (in case the selected sensor is a geodetic mark or a coordinometer base from a plumbline), or the radial, tangential and vertical displacements (in case the selected sensor is the GNSS antenna).

The sensors data was sent from LNEC, which originally consisted of six Microsoft Excel Spreadsheet (XLS) files and one Discharge Abstract Database Metadata (DAD) file (with the accelerometers data),



(a) The canvas that contains the line chart about its accelerometer data

(b) The canvas that contains the line charts with data about the temperature, water elevation and displacements

Figure 3.16: The representation of the data

Table 3.2: Categorization of the different attributes of the acquired data

Name	Ordering direction	Mark	Channel
Temperature	Diverging	Lines	2D positions
Water elevation	Sequential	Lines	2D positions
Displacements measured by leveling marks	Diverging	Lines	2D positions
Displacements measured by geodetic marks	Diverging	Lines	2D positions and color
Displacements measured by the plumblines	Diverging	Lines	2D positions and color
Displacements measured by the GNSS antenna	Diverging	Lines	2D positions and color
Accelerations measured by uniaxial accelerometers	Diverging	Lines	2D positions
Accelerations measured by triaxial accelerometers	Diverging	Lines	2D positions and color

that was later converted to CSV files through a Python script that was created. For each file read, this script starts by creating a list for each sensor of which data is present in that file, containing the lines read by that sensor. Then, for each list of lines (represented by a string), it reads the value of each attribute and edits that specific line to match the CSV format. It ends by creating a new file for each list (corresponding to its specific sensor) and writing every line from the list there.

As shown in Table 3.2, all data attributes are temporal, and so it was decided to represent them in line charts, as it is the best idiom for representing the time evolution of data, with the slope of the line giving the rate of change of the values of each attribute. It is also the ideal idiom for the data since all the keys are ordered (being all data attributes continuous). The Data Preprocessing was done for all data except the accelerometers' datasets. For dealing with missing values, it was decided to discard every record that presented at least one missing value. As the number of missing values in every dataset was significantly low, they were manually found and removed.

The outliers were found by computing the Interquartile Range (IQR) formula, ending up finding records with outliers in all the datasets. Every record that presented at least one outlier was discarded. To find and remove the outliers, a Python script was created. It computed the lower and upper ranges and removed every record that had the value of the specific attribute outside that interval. It ended by writing the values present in the final list (with all records with outliers removed) in a new CSV file.

Initially, for each CSV file read, after removing the outliers, the previous script did a roll-up operation to aggregate the data per month and another roll-up operation to aggregate the data per year, and then wrote the datasets resulting from both operations in two new CSV files. This was done for the initial implementation of the zoom-in and zoom-out features, which consisted in two selectable labels that changed from displaying the data in one CSV file to the data in another. The roll-up operations ended up being removed from the script, as it was decided to implement the zoom-in and zoom-out features in another way, as that previous approach would not guarantee an efficient analysis of the data, since it would have only three different levels of zoom. It would also result in a higher Central Processing Unit (CPU) usage, as it would have to read and process the triple of the CSV files of this new approach.

The tables containing the data visualization were initially represented as a Unity UI Canvas with a transparent background, containing for each line chart a sub canvas with a white background. The table would not stand out well from the surrounding area while having a transparent background, so a new representation of the tables was made, with them being represented as a canvas with the sub-canvas containing a white background with a black outline. Inside the white background, the graph had a sprite containing the line chart.

The creation of the content of the graphs was done by one of the two C# scripts created for that purpose. The first script was for the cases when the selected sensor was not an accelerometer, so the table would present three line charts, while the second script was for the cases when the selected sensor was an accelerometer, so the table would present one line chart. The two scripts start by reading all the data files associated with the sensors present in the virtual environment. The content of each data file is stored in a list of records, with each record corresponding to a new item in the data file. The Record struct contains the temporal data and the values of each attribute present in its corresponding item of the sensor data.

Initially, the scripts for generating the graphs created a new small Unity Sphere for each Record, with its position in its specific line chart being equivalent to its temporal and attribute values. To create the lines of each line chart, a function that connects each Sphere in the graph was created. Having to generate an extremely high number of spheres made the application run very slow once the option for plotting the data was selected, as rendering that many meshes would result in a high Graphics Processing Unit (GPU) usage. Adding this to the difficulty of manually creating interactive data visualization in C#, the use of an asset from the Unity Asset Store, called EzChart[20], was necessary to create the data tables.

This asset contained several scripts that could generate and customize many different idioms for interactive data visualization, along with chart prefabs, sprites, and shaders. Its main script was attached to the chart prefabs and contained several public attributes that could be changed to reach the wanted

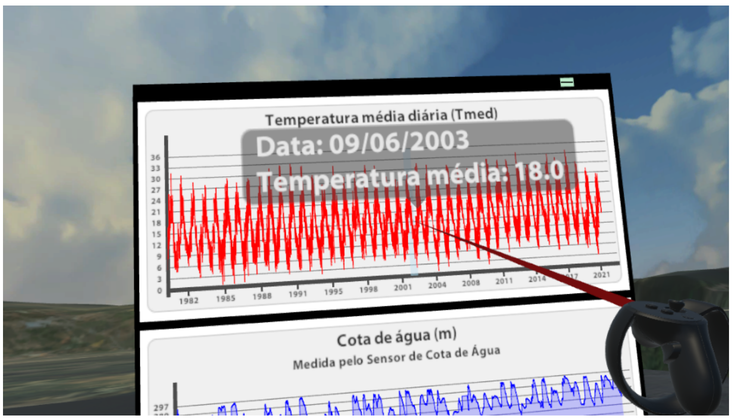


Figure 3.17: The tooltip that appears after pointing to a certain part of the line chart

[20] EzChart | GUI Tools | Unity Asset Store, https://assetstore.unity.com/packages/tools/gui/ezchart-147893, July 2022

Figure 3.18: The use of the brush feature to select a certain interval of data

way to represent the data.

The detection of the interaction with the chart canvas was originally coded in one of the EzChart scripts. This script originally detected the mouse position in the canvas. To stop detecting the mouse position and start detecting the Raycast hit from the VR controllers, this script was changed. The edited script started by detecting if the VR devices were connected, and if so, verified if either the right controller hit or the left controller hit points to a certain game object. If the pointed game object corresponds to one of the charts, the Raycast hit is processed. The implementation for detecting the Raycast hit gives priority to the hit of the right controller, so if both controllers are pointing to the same chart, the position in the canvas processed is the hit of the right controller's Raycast.

When the user points to a certain part of the line chart, a tooltip appears (Figure 3.17), displaying the attribute, its value, and the date when that value was recorded, and disappears once the user stops pointing to it. One of the scripts in this asset can be added to the prefab and contains one feature for selecting a certain interval of data with the brush tool. This feature ended up being one of the interactions with the data present in the prototype, which interaction is shown in Figure 3.18, which could be performed by pressing the 'A' button (the primary button of the right controller). This script was edited to add more interactions, such as the zoom-in, zoom-out, and the pan feature.

The zoom-in interaction is done by clicking on the 'B' button (the secondary button of the right controller) while pointing to a certain point in the line chart. After clicking, it displays 90% of the values that were present before zooming in, with the value to which the user points being in the middle, if possible. For this, the difference between the oldest value and the newest value present in the current state of the visualization was computed and then was computed the new interval (with 90% of the values). Then it was verified if the new interval was inside the limits of the dataset. If it was, that was the interval represented in the visualization, while if it was not, either the first value of the visualization was the first value of the dataset or the last value of the visualization was the last value of the dataset.

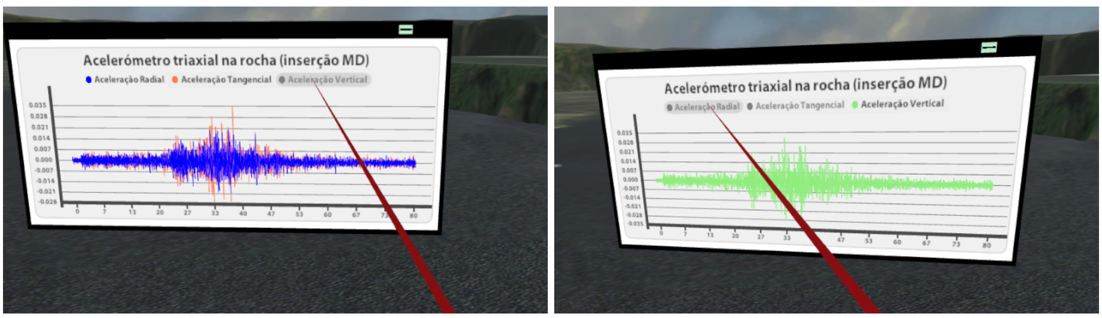
The zoom-out interaction is done by clicking on the 'Y' button (the secondary button of the left controller). After clicking, it displays values from the dataset that are temporally before and after the limits of the previously presented visualization. If one of the limits of the previous visualization was already one of the limits present in the dataset, that limit remains the same after zooming out.

The Pan interaction is done by pressing the 'X' button (the primary button of the left controller). For this two functions were implemented (one for the left movement and the other for the right movement) that are called either if the Raycast moves to the left or the right. Both functions increment or decrement the minimum and maximum values of the records date. This increase and decrease followed a value proportional to the size of the interval displayed in the visualization, to avoid high sensitivity when the zoom level is higher.

The buttons pressed by the user are detected by one of the created C# scripts and processed by another C# script that was created. This second script communicates the user's clicked button to the EzChart classes by writing the performed interaction. The EzChart classes read the text about that interaction in their update method and then perform the specific interaction in the corresponding chart, writing that the chart is updated after that.

After interacting with the data, two selectable labels appear on the line chart, one for the back option, for returning to the previous state of the visualization, and the other for the reset option, for restarting the visualization to its initial state, and disappears when the data is in its initial state. The selectable label of the reset option was already implemented in one of the EzChart scripts. Both back and reset selectable labels contain a 3D cubic mesh as their child, to detect the interaction between the Raycast hit and the selectable labels. When selected, the back and reset options call their respective functions.

The back option was implemented by storing in two public lists each minimum and maximum value of the records date, every time the visualization changed. When called, the function of the back option removes the last values of the two lists. Then it verifies if the canvas has more than one chart and if so, it does the same for each remaining chart. When the function for the reset option is called, minimum and maximum values of the records date are assigned to be the oldest and newest value of the dataset.



(a) **(b)**

Figure 3.19: The line chart of the data of a specific triaxial accelerometer with different variables selected

Those two new values are also added to their respective lists. After that, it is also verified if the canvas has more than one chart, doing the same for the remaining charts if so.

In case a certain chart has more than one attribute, it contains a legend that displays selectable labels for each different variable, containing its name and which line color represents it. The main script from EzChart was edited to add a 3D cubic mesh as a child of the legend corresponding to each variable, to detect the Raycast hit interaction. When a certain selectable label is clicked, the ToggleSeries function is called. This function toggles between showing and not showing the line corresponding to the index of the variable, as shown in Figure 3.19.

The canvas containing the charts also contains a 3D mesh as its child, to detect the Raycast interaction from the controllers. Each canvas can be moved by pressing the Trigger button of the controller that is pointing to that canvas. It can also be scaled up and down, both horizontally or vertically, by pointing both controllers to the same canvas, pressing the Triggers of both controllers and moving both joysticks.

4

Evaluation

Contents

The evaluation of VRCabrilAnalysis was divided into three different steps. First, a preliminary evaluation session was done to obtain information concerning the changes that were necessary to make in the prototype. After finishing those changes, the development of the prototype was halted during the rest of the evaluation phase. A pilot study session was done after that, to check if the evaluation methodology was viable. After correcting the detected issues in the evaluation plan, the real-user evaluation was performed, through individual sessions for each participant, to gather results concerning the benefits and consequences of applying VR technologies in dam safety analysis.

4.1 Preliminary Evaluation

The preliminary evaluation, which was performed at INESC, was done to know the necessary adaptations to be made in the prototype. It also served to detect previously undiscovered bugs, such as a bug in the Pan feature (from the data visualization features) where when reaching the most recent values, it automatically returned to the oldest values.

The representation of most of the sensor types was changed. With those changes, it would be easier to detect and recognize the sensors at greater distances, as well as distinguish the different types of sensors. Concerning the representation of the geodetic marks, their image was changed in Inkscape, ending up having the lines with a thickness of 20 millimeters, instead of the previous 5 millimeters.

Concerning the representation of the plumblines, the metallic material present in the wire of each plumbline ended up having a red color. The representation of the coordinometer bases was also changed to be more recognizable, ending up being represented more simply, with two cones containing the same material as the wire. This representation was based on DamAR.

The representation of the leveling marks also changed, since their previous representation (as a plane with the same texture as the geodetic marks) was not realistic, ending up being represented by two cylindrical meshes created in Blender and having a realistic steel material. The leveling marks were placed on top of the dam's road. The data acquisition units were removed from the scene, since they were not interactable and were too close to both the accelerometers and the geodetic marks, making it difficult to visualize all of them.

One of the changes that were decided to be made in the prototype during this phase was the position of the interactive menu. With this change, after selecting a certain sensor, the interactive menu started appearing in the middle of the HMD FOV, instead of the previous approach, where it appeared on top of the controller that was used to select the desired sensor. This change was made since having the menu on top of one of the controllers reduced the ease of interaction since it was only possible to select the desired options with one of the controllers (the opposite controller to the one that was used to select the sensor). This change also made the use of the prototype more intuitive, since the user would not see the menu after selecting the sensor in the previous approach, as its hands tend to naturally be in a position that isn't inside the HMD FOV.

The Raycast length (which was 100 before the pilot test sessions) ended up being increased to 200, to make it easier for the user to select the sensors, without being forced to move around the scene to do that. The sensors also ended up having their name on the front of them as a billboard. The representation of the billboards was based on DamAR. The material that the downstream face mesh contained after pointing to it was changed from a basic transparent material to a new material containing the downstream face texture with a transparent rendering mode to provide more realism.

Concerning the interaction with the table containing the data charts, when the option for plotting the data is selected, the data chart's initial position was changed to be on top of the intake tower. The way the user moved the table with the controllers was also changed, with the movement on the Z-axis of the left and right-hand anchors being considered, to be easier to move the table forward and backward, without the user needing to move (by using the joysticks), and avoiding the problem of having the table too close to the user's Point of View (POV) when starting to move it.

The visualization of the data concerning the displacements measured by the plumblines was wrong, with the positive displacements representing the downstream movement and the negative displacements representing the upstream movement. Since this representation was wrong, with the correct representation being positive values for upstream movement and negative values for downstream movement, the displacement values from the plumbline's data files were multiplied by -1 after being read in the C# script for the data processing of the sensors. This evolution ended up being represented as a line chart with negative values, with values ranging from -50.0 to 50.0. The meaning of the positive and negative values has also been described in the line chart.

4.2 Pilot Studies

The pilot study session was performed at LNEC, and so the desktop and VR equipment were transported from INESC to LNEC. Its objective was to determine the feasibility of the evaluation plan, as well as whether the evaluation procedure was possible to be carried out. Some changes were decided to be made in the evaluation methodology to reduce the time required for the user to understand how to use the prototype. Due to the complexity present in the VR equipment for someone new to VR, it was defined that during the real-user evaluation sessions, the users freely used the VR equipment before starting to do the tasks.

Initially, the user test script had defined that the users would try to use the VR equipment, before watching the explanatory video, and freely use the prototype between watching the video and starting the tasks. After the pilot study session, it was defined that the users would start using the VR equipment after watching the video, while the prototype was running, such that they could adapt to the VR equipment while they freely used the prototype.

4.3 User Evaluation

The user evaluation had the goal of gathering results to help in the study of the benefits and challenges related to the application of VR in the SHM of dams. In this evaluation phase, various test sessions with different participants were performed to evaluate the usability of VRCabrilAnalysis, as well as its suitability for doing tasks related to the SHM of dams.

4.3.1 Evaluation Methodology

The user evaluation took place in LNEC (Figure 4.1) and consisted of real-user tests, with LNEC staff using VRCabrilAnalysis to perform two dam safety analysis tasks, and then give feedback about the usability of the application through a questionnaire and suggestions for future work. All the test sessions (Figure 4.2) were performed individually for each user. After each test session, many participants also gave knowledgeable advice on which parts of the prototype could be improved and possible features that could be added. All the evaluation process was done in the Portuguese language since all the users were native Portuguese speakers. Each user test session followed a User Tests Protocol, containing the necessary information to correctly perform and replicate the evaluation.

For posterior evaluation concerning the usability of the prototype in the SHM of dams, as well as the usefulness and the suitability of applying VR in this field, two tasks were defined to be performed by the participants during the real-user evaluation phase. Those two tasks were described to the users as

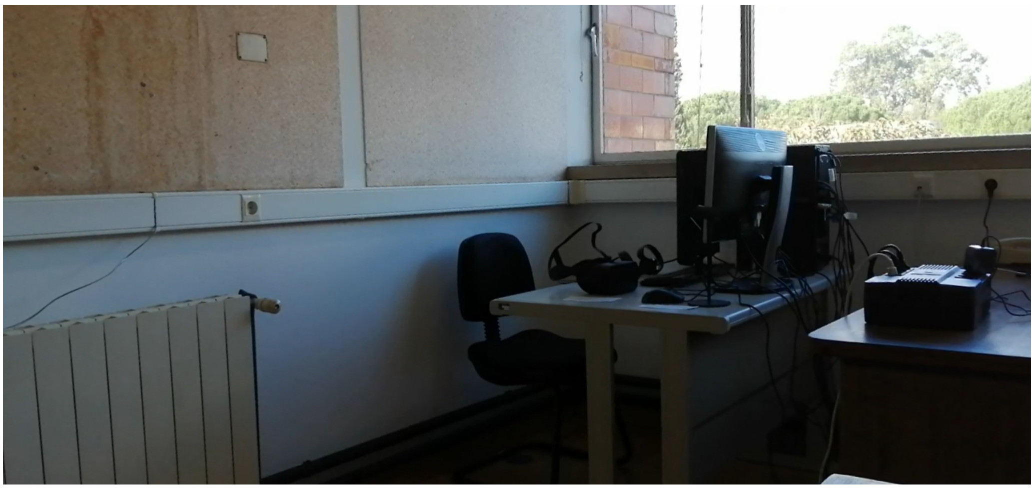


Figure 4.1: Test environment (at LNEC)

(a) **(b)**

Figure 4.2: The participants using the prototype during the real-user evaluation sessions

follows:

- T1: Determine if the maximum value of the Absolute Radial Displacement measured in Position 1 of the Plumbline FPD3 is higher or lower than 50 mm.
- T2: 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 T1 task had the goal of evaluating the benefits present in the inclusion of immersive analytics in the data analysis of dams, by evaluating the connection between the virtual environment and the 2D representation of the data. It required that the user located and selected the correct sensor and displayed its data chart, and there used the data visualization features to find the desired value.

The T2 task had the goal of evaluating the visibility of the sensors in the virtual environment and determining the easiness of recognizing and differentiating each type of sensor, as well as distinguishing each sensor between the sensors of the same type. This task required that the user located the desired sensor, and determined its name and reference, either by reading the billboard containing its name, or selecting it and reading its name in the interactive menu.

The prototype started to be run before each test task and stopped being run once the user completed each one of the test tasks. This was done to ensure that the user started each task in the initial state of the prototype (in front of the dam without having the interactive menu or any data chart opened, as well as not having any sensor selected), which ensured that users did not have different starting points in the test tasks. To evaluate the usability of the prototype, a set of metrics was registered during the real-user tests, including both objective and subjective measurements.

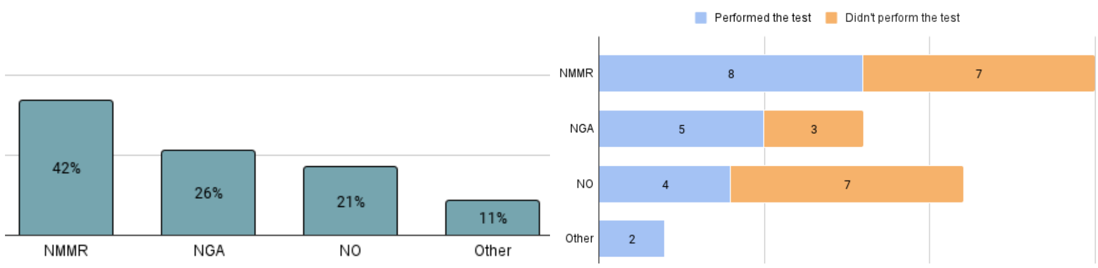
The objective measurements were the time required to complete each task (measured in seconds) and the number of wrong steps done in each task. These metrics were measured while the participant was performing the test tasks, with the screen being recorded by OBS Studio, which allowed measuring with more detail the time and number of wrong steps after the evaluation was done.

The subjective measurements involved parameters relative to the generality of the prototype, such as its User Interface (UI) friendliness, its comfort and ease of use, its utility for the SHM field, its suitability to do SHM tasks, and its level of realism and immersion. These metrics also involved more specific parameters, such as the visibility of the different sensors and their ease of selection, the ease of use of the interactive menu and the suitability of its representation, the readability of the line charts, and the ease of use of the data visualization features.

4.3.2 User Characterization

To perform the User Evaluation, the prototype was tested by 22 users, from which 19 (86%) were dam experts. Dam experts from all the investigation units from the concrete dams department participated in the study, as well as dam experts outside the concrete dams department. As shown in Figure 4.3(a), between the 19 dam experts that participated in this study, 8 (42%) belonged to the Modelling and Rock Mechanics Unit / *Núcleo de Modelação e Mecânica das Rochas* (NMMR), 5 (26%) belonged to the Applied Geodesy Unit / *Núcleo de Geodesia Aplicada* (NGA), 4 (21%) belonged to the Monitoring Unit / *Núcleo de Observação* (NO), and 2 (11%) belonged to an investigation unit outside the concrete dams department. Meanwhile, Figure 4.3(b) shows the number of members from each investigation unit that participated or didn't participate in the user evaluation.

The users were 77% men and 23% women, with an age distribution represented in Figure 4.4. The users had a high education level, with 73% having a university degree (*Licenciatura* (Lic.), Master Degree (MSc) or Doctoral Degree (PhD)), and the remaining users having a High School Diploma Graduation (HSDG), as shown in Figure 4.5. A strong portion of the users (68%) never had any contact with VR. Of the 32% of users that had contact with VR at least once, none of them owned any VR equipment, and



(a) Percentage of the investigation units that the participants belonged to

(b) Comparison for each investigation unit between the members that participated and didn't participate in the evaluation

Figure 4.3: Comparison between the number of members from each investigation unit

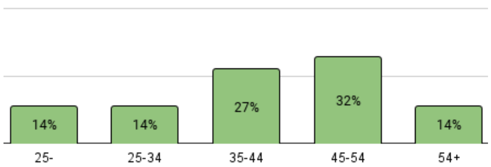


Figure 4.4: Age distribution

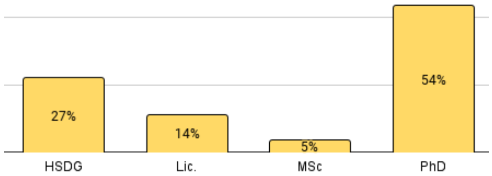


Figure 4.5: Education level distribution

only 43% used VR in a professional scope.

4.3.3 Evaluation Results

The objective usability metrics that were chosen to be measured during the realization of the tasks were the time required to complete them and the number of wrong steps done. A time limit for completing each task was set, representing the time that a dam engineer would take to complete the same task through the use of traditional methods. This time limit was based on feedback from informal interviews with experts during the pilot studies. Each time a task took more than the time limit to complete, it counted as an outlier.

- Time limit for T1: 200 s
- Time limit for T2: 30 s

As shown in Figure 4.6, the time necessary to complete T1 was significantly higher than the time necessary to complete T2. However, more users completed T1 successfully (with 95% of the users completing it before the time limit) than T2 (with 91% of the users completing it before the time limit). This might indicate that performing the analysis of dam safety data might still be a longer task to perform

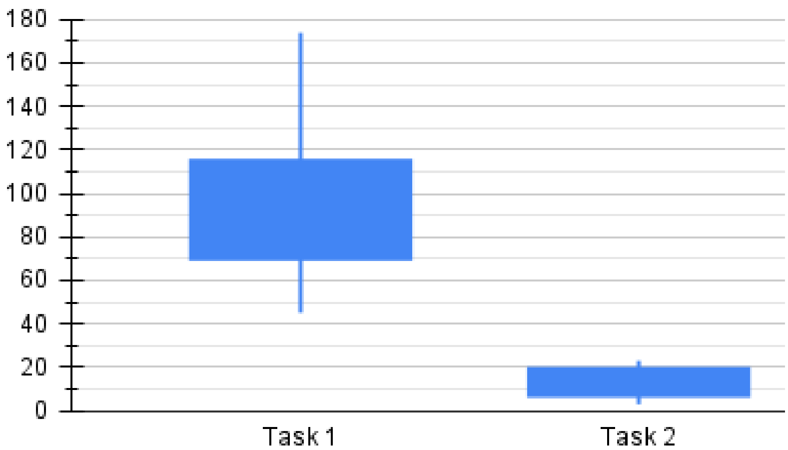


Figure 4.6: The distribution of the necessary times to complete each task

(a) Number of wrong steps on T1 **(b)** Number of wrong steps on T2

Figure 4.7: The distribution of the number of wrong steps in both tasks

by using VR than identifying the different sensors present in the dam, but that difference in time could be lower than performing them with traditional methods.

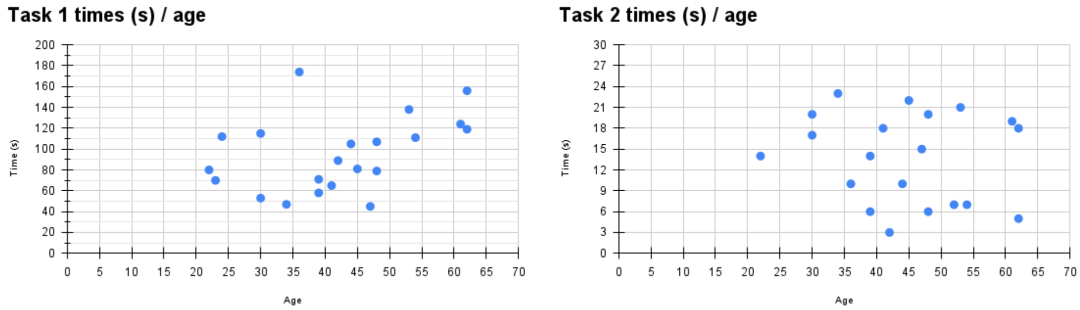
Regarding the number of wrong steps (represented in Figure 4.7), less than half of the users completed T1 without making any mistake (Figure 4.7(a)), with only 48% performing it without any wrong step. On the other hand, in T2 the results were much more positive, with 95% of the users completing the task without making any mistakes (Figure 4.7(b)). Of the 19 users that completed both tasks before the time limit, 42% of them completed both tasks without doing any wrong steps. The maximum number of wrong steps done by a single user while performing a certain task was 4 wrong steps in T1 and 2 wrong steps in T2. This might indicate that, despite the observation and identification of sensors being a simple task to perform when immersed in the virtual environment, the analysis of dam safety data might be a bit more complex to do when using VR, with the possibility of making a mistake being present during the analysis.

The different quartiles of the objective metrics are represented in Table 4.1 and show lower values in both metrics for T2 in comparison with T1. This might reinforce the possibility of the identification of the different sensors present in the dam being an easier and faster task to perform with the use of VR than the analysis of dam safety data.

As shown in Figure 4.8, two scatter plots were created representing the variation of the time required to complete T1 (Figure 4.8(a)) and T2 (Figure 4.8(b)) according to the age of the participants. None of the scatter plots showed any relevant correlation between the age and the time to complete the

Table 4.1: Minimum, First Quartile, Third Quartile, and Maximum of the objective metrics from both tasks

	Minimum	*Q1*	*Q3*	*Maximum*
Time:				
T1	45	70	115	174
T2	3	7	19.25	23
Number of wrong steps:				
T1	0	0	1	4
T2	0	0	0	2



(a) Scatter plot of T1 **(b)** Scatter plot of T2

Figure 4.8: Scatter plot representing the time measurements of both tasks from the test sessions according to the age of the participants

task, which might indicate that the ease of transiting from the use of traditional methods to the use of immersive technologies in SHM tasks would not depend on the user's age. The comparison between the number of wrong steps done in both tasks and the age of the participants also showed no relevant correlation.

As it can be seen in Figure 4.9, the mean of both the time necessary to complete each task and the count of wrong steps done while performing it was compared between participants with and without experience with VR through horizontal bar charts. In the bar charts comparing the time and number of wrong steps in T1, the results were both better for the participants that never used VR, which might

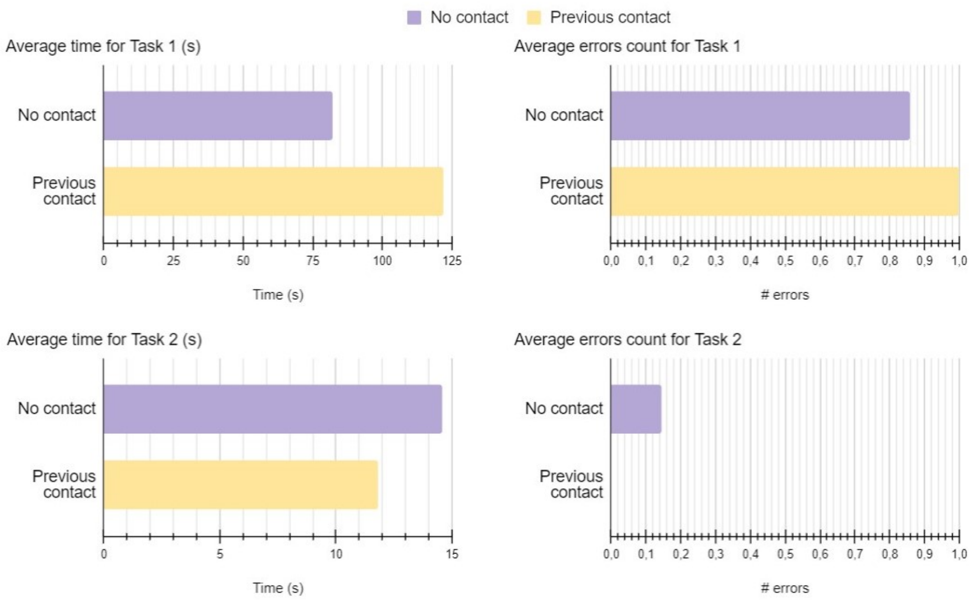
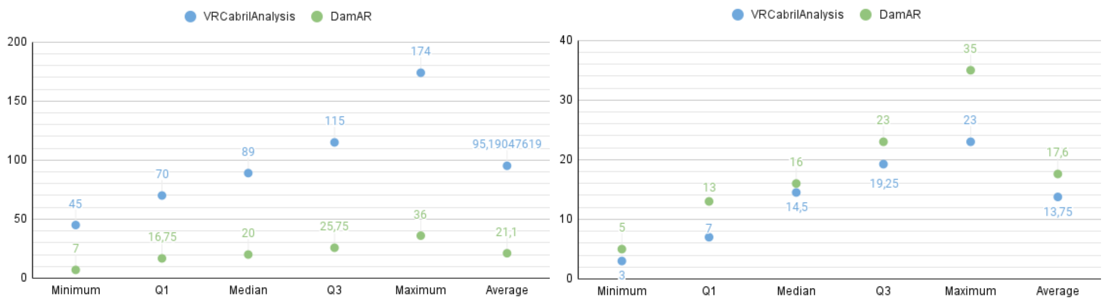


Figure 4.9: The comparison between the average time and number of wrong steps for each task between people with and without experience with VR



(a) Comparison of the time needed to complete T1

(b) Comparison of the time needed to complete T2

Figure 4.10: Comparison between the VRCabrilAnalysis user tests and the DamAR user tests, regarding the time needed to complete each task

indicate that the accessibility of immersive analytics (more precisely the visualization of data through VR) in the SHM of dams might not depend on the user's experience with VR.

In the bar charts for T2, the results, despite being both better for the participants that had previous experience with VR, were relatively similar, with the average time taken to complete T2 being in both cases less than half of the time relative to completing this type of task through traditional means. The average number of wrong steps was very low in both cases, without a single wrong step done by all the users that had previous experience with VR. This might mean that the ease of using VR to do general SHM tasks might not depend on the previous experience with VR, with the possibility of VR being a useful technology to integrate with these tasks when it comes to the ease of use, regardless of the experience that the user has with these technologies.

The test tasks from the user evaluation of DamAR were very similar to the tasks of the evaluation of VRCabrilAnalysis, with only slight differences in T1, as VRCabrilAnalysis contained different data of the displacements, with that data containing an interval of records over a longer period than the same data in DamAR. Because of this, the value of the absolute radial displacement to be compared in T1 was set as 50 mm, as it was a value that was close to the maximum displacement value in VRCabrilAnalysis data, while this value was 30 mm in T1 of the DamAR evaluation.

Since the tasks defined for the user evaluation of VRCabrilAnalysis were very similar to the tasks defined for DamAR, the results that were gathered from the evaluation of both works were compared, as shown in Figure 4.10, to determine the utility of integrating VR in the SHM of dams when compared with the integration of AR.

When comparing the results from the evaluation of VRCabrilAnalysis with the results from the evaluation of DamAR, Figure 4.10(a) shows that the time necessary for the users to complete T1 is much higher when using VRCabrilAnalysis than when using DamAR. This might indicate that the use of AR could be more accessible to include in immersive analytics than the use of VR.

Table 4.2: The results of the unpaired *t-tests* of both tasks

	Variance	*Distribution*	*p-value (%)*	*Significant difference (lower than 5%)*
Time:				
T1	Unequal	Two-tailed	3.95×10^{-7}	Yes
T2	Equal	Two-tailed	3.16×10^{1}	No
Number of wrong steps:				
T1	Equal	Two-tailed	1.00×10^{1}	No
T2	Equal	Two-tailed	4.66×10^{1}	No

Regarding the results from T2, Figure 4.10(b) shows that the time necessary to complete that task is slightly lower when using VRCabrilAnalysis than when using DamAR. This might indicate that the identification, analysis, and interaction with the sensors could be a faster and easier process to perform with the use of VR than with the use of AR.

To understand if there is a statistically significant difference between the results of VRCabrilAnalysis and the results of DamAR, unpaired *t-tests* were performed on the four objective measures from the evaluation of both prototypes (Table 4.2), with the significance level being set to 5%. Before the unpaired *t-tests*, the Levene tests were calculated to determine the variance of the different objective measures, concluding that all measures had an equal variance, except the times from T1.

By analyzing the p-value (computed as a result of the unpaired *t-tests*), it was concluded that only the times from T1 had a statistically significant difference between the use of VRCabrilAnalysis and the use of DamAR. The two tasks having different outcomes suggest the necessity of performing additional tests to obtain meaningful conclusions regarding the use of VR in dam health monitoring. The evaluation of VRCabrilAnalysis should be more widespread in the future, with the user tests containing more tasks and having more participants, contributing to a larger sample size.

The subjective usability metrics were gathered through a feedback questionnaire, that was filled out by the user after completing the tasks. This questionnaire contained 22 questions using a Likert scale between 1 (totally disagree) and 5 (fully agree). Those questions encompassed the general use of the prototype and its usability to do the tasks, as well as more specific areas of the prototype such as its sensors, the interactive menu, the data visualization features, and its level of immersion and realism. The first quarter, median, third quarter and IQR of the responses to each question of the questionnaire can be seen in Table 4.3.

Regarding the generality of the prototype, the majority of users considered the prototype to have a friendly UI (54% voted 5, 41% voted 4 and 5% voted 3) and to be comfortable to use (55% voted 5, 36% voted 4 and 9% voted 3) but didn't had a so favorable opinion regarding the ease of use (32% rated 5, 50% rated 4 and 18% rated 3). Most of the users considered the prototype to be useful for sensor data analysis (59% voted 5, 23% voted 4 and 18% voted 3), and the vast majority of them saw potential in it to be useful for dam safety control tasks (59% rated 5, 36% rated 4, and 5% rated 3).

Regarding the usability of the prototype to do the tasks, the majority of the users considered that

Table 4.3: First Quartile, Median, Third Quartile, and Inter-quartile Range of the answers to the feedback questionnaire

	Q1	*Median*	*Q3*	*IQR*
Regarding the generality of the prototype:				
Has a friendly UI	4	5	5	1
Is comfortable to use	4	5	5	1
Is easy to use	4	4	5	1
I consider the prototype useful for sensor data analysis	4	5	5	1
I see potential in this prototype to be useful in the future in supporting dam safety control tasks	4	5	5	1
Regarding the tasks:				
Was easy to perform task A (comparing the values in the graph)	4	5	5	1
Was easy to perform task B (identify geodetic mark)	5	5	5	0
Regarding the sensors:				
Is easy to distinguish each type of sensor	4	5	5	1
Is easy to distinguish between different sensors of the same type	4.25	5	5	0.75
Is easy to select each sensor	4	4.5	5	1
Is easy to identify the name/reference of the sensor	4	5	5	1
The sensors have adequate dimensions	5	5	5	0
Regarding the interactive menu:				
Is easy to use	4	5	5	1
Has adequate colors and icons	5	5	5	0
Has adequate dimensions	5	5	5	0
Regarding the data charts:				
The graphs are easy to read	4	5	5	1
Was easy to find the desired information	4.25	5	5	0.75
The colors and dimensions are adequate	5	5	5	0
The data visualization features (approximate/zoom and move/pan) are easy to use	4	5	5	1
Immersiveness and realism:				
The representation of the Cabril dam is realistic	4	5	5	1
The representation of the area surrounding the dam is realistic	4	5	5	1
I felt immersed in the experience	4	5	5	1

the tasks were easy to do through the use of the prototype. For the ease of doing the T1 task, 68% rated 5, 22% rated 4, 5% rated 3, and 5% rated 2. The T2 task was even easier for the users to do while using the prototype, with 86% rating 5 and 14% rating 4, which could reinforce the possibility of the identification of sensors being an easier task to perform using VR than the analysis of data.

When it comes to the representation of the sensors in VRCabrilAnalysis, the vast majority of the opinions were favorable on all aspects, with the majority of users considering the different sensor types to be easy to distinguish (68% rated 5, 23% rated 4, and 9% rated 3), and is even easier to distinguish between the sensors of the same type (73% rated 5 and 27% rated 4), which may imply the importance that the billboards containing their names have in the identification of the sensors. The majority of the users considered that the sensors were easy to select (50% rated 5, 41% rated 4, and 9% rated 3), easy to identify their name and reference (64% rated 5, 32% rated 4, and 4% rated 2), and had adequated dimensions (82% rated 5 and 18% rated 4).

Concerning the interactive menu, most of the users considered it to be easy to use (68% rated 5, 18% rated 4, and 14% rated 3), and the vast majority considered it to have adequated icons and colors

(82% rated 5, 9% rated 4, and 9% rated 3), and to have adequated dimensions (86% rated 5 and 14% rated 4).

Regarding the data charts, the vast majority of users considered that they were easy to understand (59% rated 5, 36% rated 4, and 5% rated 3), easy to find the desired information (73% rated 5 and 27% rated 4), and that they had adequated colors and dimensions (77% rated 5, 18% rated 4, and 5% rated 3). The vast majority of users also found the data visualization features to be easy to use (68% rated 5, 27% rated 4, and 5% rated 3).

Concerning the realism present in VRCabrilAnalysis, the vast majority of users considered that the representation of the Cabril dam was realistic (59% voted 5, 36% voted 4 and 5% voted 3), but didn't have an opinion so favorable regarding the realism present in the representation of the surrounding area (54% voted 5, 32% voted 4, 9% voted 3 and 5% voted 2). Also, regarding the immersion present in the prototype, the vast majority of the users felt immersed in the experience (59% voted 5, 36% voted 4 and 5% voted 3).

4.4 Discussion

The main goal of the user evaluation was to obtain information concerning the utility and the applicability of VR in the SHM of dams, more specifically in dam safety control. The participants were very pleased with the usability of the prototype and interested in the possibilities and potential that the consequent development of VRCabrilAnalysis and other VR applications for dam safety analysis can present.

The participants did not have any significant difficulties when performing the test, with the vast majority of them completing both tasks before the time limit. Both the T1 task, related to the analysis of dam safety data, and the T2 task, related to the visualization and identification of the sensors, took on average less than half of the time a user would take to perform those tasks through traditional methods. However, there was a significant discrepancy between the lowest and the highest times of T1, possibly due to the difficulty some users had in selecting the coordinometer base from the FPD3 plumbline, both because its format made it difficult to be selected and because the buttons for selecting and teleporting were sometimes clicked accidentally.

The results from both tasks were very positive, especially because around two-thirds of the users never had any contact with VR, but quickly understood how to use the equipment and the features of the prototype by watching the exemplifying video and freely using the prototype before starting to do the tasks. According to the participants, freely using the prototype helped them to understand much more how to use both the VR equipment and the prototype itself, than watching the exemplifying video, which might determine that is easier to perceive something by interacting with it than by seeing it. The participants who had previous contact with VR had ease and speed of adaptation to the prototype similar to the participants with no experience with VR, being their registered times and their number of errors also similar.

The participants found the prototype to be comfortable to use and have a friendly UI. Their least favorable opinion was related to the general ease of use of the prototype. The vast majority of the participants found it easy to interact with the menu and with the data charts. However, some of them found it harder to select the sensors, with some types of sensors, such as the coordinometer bases of the plumblines, having a format that made them difficult to be selected through Raycast. Some users also mentioned the difficulty they had in finding the sensors that were present in the most lateral blocks of the dam.

The participants never used the instructions table, possibly because it needed to be opened by clicking on its option in the menu, instead of being already present in the virtual environment. Some participants mistakenly selected the wrong button between the teleportation and the selection ones. With this, together with the ease that the vast majority of users felt regarding the controller-based locomotion, it is possible to consider that controller-based locomotion could be the better locomotion technique to use in VR applications concerning the field of SHM when compared with teleportation-based locomotion.

In addition to the opinion of the participants on the current state of the prototype, expressed when filling out the feedback questionnaire, most of the participants also gave knowledgeable advice and suggestions for future improvement, through informal interviews. This was valuable information for the future work of VRCabrilAnalysis, due to their high knowledge in the SHM field.

5

Conclusions

Contents

This work explored the benefits and challenges associated with the integration of VR technologies in dam health monitoring. In particular, it studied the efficiency and applicability that VR technologies have in tasks of dam analysis and dam safety control when compared with traditional means. This work also explored how useful the application of these technologies in immersive analytics could be.

This study was supported by the development and evaluation of a VR prototype called VRCabrilAnalysis, which allows the user to visualize the Cabril dam, interact with its sensors, and analyze the data measured by each sensor, while inside a virtual environment resembling the Cabril area. This prototype was developed as a proof of concept and will be continued in future projects. Its main objective is to serve as a starting point for the development of VR applications in the scope of dam health monitoring.

After its development, the prototype was evaluated through individual sessions with real users, to get results concerning the usability and applicability of these technologies in dam analysis and dam safety control tasks, as well as feedback from dam experts on what could be changed and improved in the prototype for the future projects. This work contributed to a poster for the ICGI 2022 conference.

5.1 Achievements

The greatest achievement of this work was its contribution to the development of VR applications integrated into the field of dam monitoring. VRCabrilAnalysis serves as a starting point for future projects, namely the works that are being developed by the students Raquel Chin and Tomás Sequeira.

Another achievement of this work was the demonstration that VR technologies can be effectively applied in the field of dam health monitoring. It was concluded that dam engineers could perform tasks of dam analysis and dam safety control using VR faster than performing it using traditional methods, regardless of their experience with VR. Exploring the effectiveness and usefulness of applying VR in dam engineering was one of the objectives of this project.

VRCabrilAnalysis met the main requirements from LNEC. These requirements included a coherent representation of the Cabril dam, as well as its surrounding area. The modeling of the dam resulting in a model coherent with the Cabril dam in real life was one of the most important objectives of this work, due to the lack of access to an existing model. A coherent representation of the surrounding area was also important to make the user feel immersed in a virtual environment that would be as similar to reality as possible.

Another important requirement from LNEC was to have a correct representation of the Cabril dam sensors, with their blocks and elevations in the virtual environment being equivalent to their blocks and elevations in real life, and also to have different types of sensors represented. In VRCabrilAnalysis, the users can visualize and interact with geodetic marks, plumblines (and their respective coordinometer bases), the GNSS antenna, accelerometers (either uniaxial or triaxial), leveling marks, and one water elevation sensor. By clicking on each sensor, an interactive menu appears, in which the user can choose if he wants to plot the data measured by that sensor, read more information about the sensor and its last recorded values, or expand the instructions table.

Having an adequate representation of the sensors data was another requirement from LNEC, and therefore was one of the objectives of this work. The data that can be visualized and analyzed in VRCabrilAnalysis includes the evolution of the displacements (radial, tangential, and vertical), the temperature, and the water elevation over the years, as well as the accelerations (radial, tangential, and vertical) measured by the accelerometers during a specific earthquake. All the data in VRCabrilAnalysis is represented as line charts, and include features for increasing and decreasing the granularity (Zoom-In and Zoom-Out), moving temporally with the panning feature, and selecting a certain interval of time with the brush feature.

5.2 Limitations and Future Work

During the development of VRCabrilAnalysis, some limitations were faced, such as not having access to an existing model of the Cabril dam, and therefore having the necessity to create it from PLY files provided by LNEC. The process of creating a model that was coherent with the Cabril dam consisted of four primary phases.

The first phase of creating the dam model was sampling the chosen point cloud from the various PLY files received. The second phase was creating the mesh from the sampled point cloud and was the most time-consuming phase during the creation of the dam model, as several approaches were followed to correctly create the mesh, with different Meshlab algorithms and Python scripts being tried for that purpose. The third phase was mapping the UV coordinates to the created mesh, to correctly apply the texture to it in Unity. The final phase was integrating the created model into the virtual environment, along with its surrounding area.

Being VRCabrilAnalysis a prototype that serves as a proof of concept, it will be continued in future projects, such as the projects from the students Raquel Chin and Tomás Sequeira. VRCabrilAnalysis has the limitation of only working offline. This prototype is not yet collaborative and the data to be analyzed by the users is static, and not dynamic, with the last values being from 2021. These are aspects that were considered for future work, being this prototype intended to be an application of collaborative VR in future projects, having its data updated in real-time. One of the goals of this work in the future is to be a first step towards a digital twin VR application of the Cabril dam, which could allow users to analyze and monitor its structural health in real-time and then act accordingly.

By being an application of collaborative VR in the future, some features could be useful to be developed to facilitate collaborative work. One of them is the possibility to write notes inside the virtual environment, which could improve communication between the users. Another useful feature is the possibility to capture and share in the virtual environment what is being seen.

From the user evaluation, by analyzing the results regarding the subjective metrics (acquired from the feedback questionnaire), the least favorable opinions were related to the ease of use of VRCabrilAnalysis. Because of this, one of the improvements in the prototype that were considered for future work was to make VRCabrilAnalysis easier to use.

During the evaluation sessions, all the suggestions that the participants gave for the improvement of the prototype were considered for future work. Of the 22 participants, two of them suggested the possibility of having two tables opened at the same time, as the current state of the prototype can only have one table opened between the accelerometers and one table opened between the other types of sensors. One example in which this improvement is useful, that is a common practice during the analysis of the Cabril dam through traditional methods, is to have the tables related to the data of the two weighted plumblines (FPD1 and FPD3) to compare the evolution of the displacements measured by both plumblines.

Some suggestions were related to the visibility of the interface components. Since the tables with the sensor data appeared on top of the intake tower when the option for displaying the data was selected, many participants found themselves in a position far from the intake tower and so they couldn't see where the table with the data was, feeling that nothing happened when the option for displaying the data was selected. To solve this issue during future work, one of the participants suggested making the graphics tables appear in the middle of the user's POV (like the interactive menu), or next to the user's position at the time. One of the users suggested making the billboard with the name more noticeable when pointing to a certain sensor, and another participant suggested increasing the size of the values in the Y-axis when the user moves away from the table.

There were suggestions related to the UI of VRCabrilAnalysis. One of the participants suggested an option for choosing the types of sensors to appear in the environment. This could make it easier for the users to find a particular sensor. Two participants suggested a button defined for moving the user to the initial position. This could be a useful improvement, as various users accidentally teleported to a certain location when trying to select something during the evaluation, as the buttons for both actions were similar, ending up not knowing where they were in the virtual environment.

One of the participants gave a suggestion related to the level of realism and immersion of VRCabrilAnalysis, which was the inclusion of ambient noise. One of the participants gave various suggestions regarding the data visualization, which were the creation of a way to check the observation history, a feature to only see data from a certain inspection, and a feature for selecting a certain limit for the values, having the values that were higher than that limit appearing with a different color.

Many participants found the representation of their controllers inside the virtual environment to be confusing, as the representation of their hands didn't appear, and so they didn't know which button they were clicking (which contributed to the participants accidentally teleporting when they wanted to select something, as mentioned previously). Because of this, one of the improvements for future work is to have an effective representation of the user's hands in the environment, as well as their movement.

Most of the users had difficulties selecting the required coordinometer base during the T1 task in the user tests. Concerning this, two participants suggested having a spherical collider around the coordinometer bases, which could make them easier to be selected through Raycast. Two users also suggested having a different font for the billboards, such that the sensor names could become more visible. One of the users suggested that the menu should appear further, blocking a lower portion of the visualization.

In the future, the model of the Cabril dam could include different types of dam failures (such as cracks or strains), which could improve the realism of VRCabrilAnalysis. This could also prove useful for the tasks of dam safety control, as the user could point to those failures through Raycasting, displaying information about each anomaly by selecting it. Another feature that could prove useful for dam analysis is an option to see the visual evolution of the dam over the years, which could only be possible by having sets of several photos of the dam for each year, to be orthorectified, as well as point clouds from yearly laser scannings. In future work, rather than having the entire dam's downstream face transparent when the user is pointing to it, it is intended to only become transparent the block to which the user is pointing.

As the accelerometers only show data from one specific earthquake at the current state of the prototype, one possible improvement for future analysis is to have an option for selecting one specific earthquake to analyze its accelerations measured by the selected accelerometer. This option could appear after selecting the option to display the data, present in the interactive menu, when selecting one of the accelerometers.

5.3 Final Remarks

This work is a first step towards the development of an effective VR application for dam health monitoring. The main goal of this prototype in the future will be to transform it into a collaborative VR application, to allow collaborative work between multiple dam engineers in a collaborative virtual environment. This could improve communication and teamwork in the different tasks associated with the analysis and monitoring of dams.

This work showed that VR technologies can be applied in dam health monitoring, facilitating the tasks of dam analysis and dam safety control, when compared with the use of traditional means, regardless of the user's experience with VR. With the continuous evolution that immersive technologies have had in multiple areas, the SHM could benefit a lot in the future from VR applications.

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A

User Tests Protocol

This appendix contains the user tests protocol, that was followed during the tests and has the goal of enabling the replication of the user evaluation.

User Tests Protocol

Materials

- Chair and desk;
- Disinfectant and paper;
- Cell phone and tripod;
- Hardware:
  - Computer with:
    - Processor = Intel(R) Core(TM) i7-8700 CPU @ 3.20GHz
    - Graphics card = NVIDIA GeForce GTX 1060 3GB
    - RAM = 16GB
  - VR equipment (Oculus Rift and Touch):
    - Rift Headset
    - Two sensors
    - Left Touch and Right Touch controllers
- Software:
  - Unity:
    - Version = 2021.2.18f1
  - Prototype:
    - VRCabrilAnalysis
  - OBS Studio:
    - Version = 27.2.4
  - Oculus Software:
    - Version = 46.0.0.230.0

Setup

- Build the computer;
- Position the chair next to the computer to give the participant some room to move while using the prototype (seated);
- Remove all objects that may collide with the participant while using the VR equipment;
- Place the two VR sensors such that the distance between them is between 1m and 2m, and ensure that they detect an area of at least $1m^2$;
- Make sure no objects are blocking the line of sight between the VR headset and the sensors;
- Clean the work environment and disinfect the equipment;
- Open the three questionnaires on the computer;
- Open Unity and chose the VRCabrilAnalysis program, and select Game View;
- Open OBS Studio to record the use of the prototype during the tests, to be able to register the necessary data for the study;
- Present the exemplifying video on the computer;
- Use the cell phone (placed on the tripod) in case the user agreed to be photographed or filmed;

Methodology

- **Introduction:**
  - Welcoming the participant and giving a brief presentation of the project (2 min);
  - The participant fills out a consent form, to determine if he accepts to be photographed and filmed during the session (1 min);
  - The participant fills out a user characterization form (1 min);
- **User training:**
  - Presenting the exemplifying video, that explains how to use the prototype (3 min);
  - Giving the VR equipment to the participant and start running the prototype, such that the participant can freely use the prototype, to better understand how to interact with both the prototype and the VR equipment (12 min on average);
- **Performing of tasks:**
  - Presenting the two test tasks to the participant, starting by presenting Task 1, and once the participant has completed it, presenting Task 2, with the tasks always following the same order (the time to present both tasks and the participant completing them is a maximum of 5 min);
  - Tasks:
    - **T1:** Determine if the maximum value of the Absolute Radial Displacement measured in Position 1 of the Plumbline FPD3 is higher or lower than 50 mm.
    - **T2:** 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 prototype is in the initial state before each test task, starting to run once the task starts and stopping running once the participant completed that task. This ensures that the user starts each task in the initial state of the prototype, not having any different starting points from other users in the second task.
- **Post-test questionnaire:**
  - The participant fills out a final form, for feedback about his opinion on the prototype's usability and the execution of the tasks (2 min);
  - Ask the participant if he has any suggestions to improve the prototype (2 min);
  - Thank the participant for the time spent (1 min).
- The total duration of each session will not exceed 30 minutes.

Usability Metrics

- **Objective measurements:**
  - Time required to complete each task (in seconds);
  - Number of wrong steps in each task;
- **Subjective measurements:**
  - UI friendliness;
  - The comfort of use;
  - Ease of use;
  - Utility for the SHM field;
  - Suitability to do SHM tasks;
  - Visibility of the different sensors and their ease of selection;
  - Ease of use of the interactive menu and the suitability of its representation;
  - Readability of the line charts;
  - Ease of use of the data visualization features;
  - Realism;
  - Immersiveness;

User Test Script (in Portuguese, since all the participants were Portuguese)
- Bom dia. Bem vindo aos testes de usabilidade para a minha dissertação de mestrado.
- Irá ser testado um protótipo de Realidade Virtual, chamado VRCabrilAnalysis, que permite a visualização e análise de dados medidos pelos sensores presentes na barragem do Cabril.
- Irá começar por preencher um formulário de consentimento, para indicar se aceita ser fotografado e filmado enquanto realiza o teste. As fotografias, áudio e vídeos obtidos irão ser usados para documentar os testes de utilização.
- Irá agora preencher um questionário de caracterização de utilizadores.
- Vou agora mostrar o vídeo exemplificativo, que explica como usar as diferentes funcionalidades do protótipo.
- Agora vou começar a correr o protótipo. Para já, irá utilizá-lo livremente, para perceber melhor como utilizar uma aplicação de Realidade Virtual, antes de procedermos aos testes.
- Agora irá realizar os testes. Estes testes consistem na realização de duas tarefas de visualização dos sensores e análise dos seus dados.
- Relembro que esta aplicação é um protótipo, pelo que continuará a ser desenvolvida no futuro e poderá ter falhas durante a sua utilização, sendo que no caso de não conseguir completar uma tarefa, significa que a aplicação precisa de ser melhorada nesse aspecto, pelo que qualquer dificuldade encontrada durante o teste ajudará a melhorá-la.
- Agora irá preencher um questionário para feedback da aplicação.
- Obrigado pela sua disponibilidade na realização dos testes.

Documents:
- Exemplifying video: https://streamable.com/kdvenu
- Consent form: https://docs.google.com/forms/d/e/1FAIpQLSeFphBDsiHoCvLatQhvjLBCcwgMpovVNtHZjB9HYBrKiKOFcg/viewform
- User characterization form: https://docs.google.com/forms/d/e/1FAIpQLSc2yWmTNvYKiULRPwXGXg1Scef6sj3cQSWn220YgFMpPSjnOw/viewform
- Feedback form: https://docs.google.com/forms/d/e/1FAIpQLSfu4_WkTdhd9GMkMmBBGl4mAs0S-aQUiBG0jZFKByBVDKM9fg/viewform

Preliminary evaluation was done in:
- Date: 22/11/2022
- Hour: 10:00

Pilot studies were done in:
- Date: 07/12/2022
- Hour: 11:30

User tests were done in:

User	Date	Hour
User 1	12/12/2022	14:30
User 2	12/12/2022	15:20
User 3	15/12/2022	11:30
User 4	15/12/2022	12:10
User 5	15/12/2022	14:10
User 6	15/12/2022	16:30
User 7	15/12/2022	17:00
User 8	15/12/2022	17:40
User 9	16/12/2022	11:40
User 10	16/12/2022	12:20
User 11	16/12/2022	15:40
User 12	16/12/2022	16:30
User 13	19/12/2022	11:40
User 14	19/12/2022	14:40
User 15	19/12/2022	15:20
User 16	21/12/2022	10:20
User 17	21/12/2022	11:20
User 18	21/12/2022	12:20
User 19	21/12/2022	14:20
User 20	21/12/2022	14:40
User 21	22/12/2022	11:20
User 22	22/12/2022	12:00

B

Forms

This appendix includes the three questionnaires that were filled out by the participants during the user evaluation phase.

Consent Form

(in Portuguese, since all the participants were Portuguese)

Caro participante.

O nosso estudo consiste em investigar os benefícios e consequências de aplicar tecnologias de Realidade Virtual na análise da segurança de barragens. Para tal precisamos da sua contribuição.

Neste estudo irá testar uma aplicação de Realidade Virtual chamada VRCabrilAnalysis, realizando duas tarefas relacionadas com a análise de dados dos sensores presentes na barragem do Cabril. Irá também preencher um questionário de caracterização de utilizadores antes de se dar início aos testes de usabilidade, bem como um questionário para feedback da aplicação, ao concluir os testes. No caso de permitir, iremos fotografar e filmar o decorrer dos testes, de modo a conseguirmos obter informações mais específicas que irão suportar a análise dos resultados.

Toda a informação obtida, incluindo imagens, áudio e vídeos, irão ser usadas confidencialmente e não serão partilhadas, podendo no entanto ser usadas para análise estatística e para fins científicos.

A sua autorização para participar neste estudo é voluntária, pelo que poderá, caso queira, recusar e abandonar a sessão em qualquer altura.

Para participar neste estudo, pedimos que preencha este formulário de consentimento, que tem uma duração aproximada de 1 minuto.

Agradecemos a sua colaboração.

Eu li e entendi o significado deste estudo. Terei a oportunidade de colocar questões, se necessário, e obter as respostas correspondentes:
(obrigatório escolher uma das opções)

○ Concordo ○ Discordo

Eu entendo que a participação neste estudo é voluntária e que eu posso desistir do mesmo a qualquer altura:
(obrigatório escolher uma das opções)

○ Concordo ○ Discordo

Eu autorizo a obtenção de informação durante a sessão de testes sob a forma de:
(marque todas que se aplicam)

- ☐ Fotografias
- ☐ Vídeos
- ☐ Áudio
- ☐ Nenhuma das anteriores

Eu autorizo o uso de dados obtidos durante a sessão de testes, que serão utilizados para calcular as diferentes métricas de usabilidade da aplicação:
(obrigatório escolher uma das opções)

○ Autorizo ○ Não autorizo

Eu autorizo o processamento dos dados obtidos para análise, pesquisa e divulgação de resultados em publicações científicas ou conferências na área de projeto, por investigadores deste projeto:
(obrigatório escolher uma das opções)

- ○ Autorizo
- ○ Não autorizo

Eu entendi que os dados obtidos neste estudo irão ser usados da forma mencionada acima:
(obrigatório escolher uma das opções)

- ○ Concordo
- ○ Discordo

Eu entendi que a qualquer momento eu posso ter acesso aos meus dados pessoais obtidos neste estudo, ao contactar o principal investigador deste projeto via email:
(obrigatório escolher uma das opções)

- ○ Concordo
- ○ Discordo

Como descrito acima, eu autorizo a minha participação neste estudo e aceito as suas condições:
(obrigatório escolher uma das opções)

- ○ Autorizo
- ○ Não autorizo

User Characterization Form
(in Portuguese, since all the participants were Portuguese)

Este questionário tem uma duração aproximada de 1 minuto, e tem o objetivo de registar o perfil e as características demográficas do utilizador. Toda a informação obtida a partir deste questionário será tratada de forma confidencial, sendo usada unicamente para fins académicos. Agradecemos a sua disponibilidade e tempo para participar.

Género:
(obrigatório escolher uma das opções)

- ○ Feminino
- ○ Masculino
- ○ Outro
- ○ Prefiro não dizer

Idade:
(obrigatório responder)

Grau de escolaridade:
(obrigatório escolher uma das opções)

- ○ Ensino secundário
- ○ Licenciatura
- ○ Mestrado
- ○ Doutoramento
- ○ Nenhuma das anteriores

Já teve contacto com Realidade Virtual?
(obrigatório escolher uma das opções)

○ Sim ○ Não

Experiência com Realidade Virtual
(responda às próximas duas perguntas apenas se respondeu “Sim” à pergunta anterior)

Possui algum equipamento de Realidade Virtual?
(obrigatório escolher uma das opções)

○ Sim ○ Não

Já teve contacto com Realidade Virtual num contexto profissional?
(obrigatório escolher uma das opções)

○ Sim ○ Não

Área profissional

Trabalha na área de barragens?
(obrigatório escolher uma das opções)

○ Sim ○ Não

Núcleo do departamento de barragens
(responda à próxima pergunta apenas se respondeu “Sim” à pergunta anterior)

Em que núcleo do departamento de barragens trabalha?
(obrigatório escolher uma das opções)

○ NO (Núcleo de Observação)

○ NGA (Núcleo de Geodesia Aplicada)

○ NMMR (Núcleo de Modelação e Mecânica das Rochas)

○ Outro

Feedback Form
(in Portuguese, since all the participants were Portuguese)

Este questionário tem uma duração aproximada de 2 minutos, e tem o objetivo de registar a sua opinião acerca do teste que acabou de realizar, bem como do funcionamento geral do protótipo. Toda a informação obtida a partir deste questionário será tratada de forma confidencial, sendo usada unicamente para fins académicos. Agradecemos a sua disponibilidade e tempo para participar.

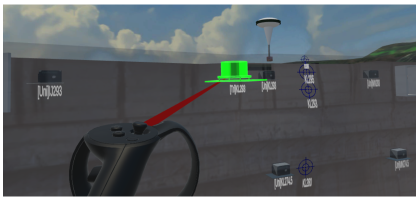
Relativamente ao protótipo:
(marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Tem uma interface amiga do utilizador	O	O	O	O	O
É cómodo	O	O	O	O	O
É fácil de utilizar	O	O	O	O	O
Considero o protótipo útil para a análise de dados dos sensores	O	O	O	O	O
Vejo potencial neste protótipo para de futuro ser útil no apoio a tarefas de controlo da segurança de barragens	O	O	O	O	O

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)	O	O	O	O	O
Foi fácil realizar a tarefa B (identificar marca geodésica)	O	O	O	O	O

Relativamente aos sensores:
(marque apenas uma opção em cada linha)

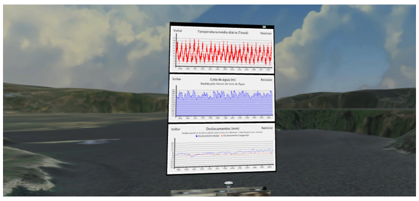


	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
É fácil distinguir cada tipo de sensor	○	○	○	○	○
É fácil distinguir entre os vários sensores do mesmo tipo	○	○	○	○	○
É fácil selecionar cada sensor	○	○	○	○	○
É fácil identificar o nome/referência do sensor	○	○	○	○	○
Os sensores possuem dimensões adequadas	○	○	○	○	○

Relativamente ao menu interativo:
(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 dimensões adequadas	○	○	○	○	○

Relativamente aos gráficos das grandezas observadas:
(marque apenas uma opção em cada linha)



	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
Os gráficos são de fácil leitura	○	○	○	○	○
Foi fácil encontrar a informação desejada	○	○	○	○	○
As cores e dimensões são adequadas	○	○	○	○	○
As funcionalidades de visualização de dados (aproximar/zoom e mover/pan) são fáceis de utilizar	○	○	○	○	○

Imersividade e realismo:
(marque apenas uma opção em cada linha)

	1 - Discordo Totalmente	2	3	4	5 - Concordo Plenamente
A representação da barragem do Cabril é realista	○	○	○	○	○
A representação da área em volta da barragem é realista	○	○	○	○	○
Senti-me imerso na experiência	○	○	○	○	○

C

Raw Data

This appendix contains the data collected during the evaluation phase.

Raw Data

User:	Gender:	Age:	Education:	Contact with VR:	Owned any VR equipment:	Used VR in a professional scope:	Worked in the dam area:	Nucleus:
User 1	Male	30	MSc	No contact	-	-	Yes	NMMR
User 2	Male	42	Lic.	No contact	-	-	Yes	NMMR
User 3	Female	54	PhD	Previous contact	No	Yes	Yes	NO
User 4	Male	30	PhD	No contact	-	-	Yes	NMMR
User 5	Male	62	HSDG	No contact	-	-	Yes	NO
User 6	Male	47	PhD	No contact	-	-	Yes	NMMR
User 7	Male	24	Lic.	Previous contact	No	No	No	-
User 8	Male	61	PhD	Previous contact	No	Yes	Yes	NGA
User 9	Male	39	PhD	No contact	-	-	Yes	NO
User 10	Female	36	PhD	Previous contact	No	No	Yes	NGA
User 11	Male	48	HSDG	No contact	-	-	Yes	NMMR
User 12	Male	53	HSDG	No contact	-	-	Yes	NMMR
User 13	Male	44	PhD	Previous contact	No	Yes	Yes	NO
User 14	Male	41	PhD	No contact	-	-	Yes	NMMR
User 15	Male	52	HSDG	No contact	-	-	Yes	NGA
User 16	Female	62	PhD	Previous contact	No	No	Yes	NGA
User 17	Male	45	PhD	No contact	-	-	Yes	Other
User 18	Female	22	Lic.	No contact	-	-	No	-
User 19	Male	48	HSDG	Previous contact	No	No	Yes	NGA
User 20	Female	23	HSDG	No contact	-	-	No	-
User 21	Male	39	PhD	No contact	-	-	Yes	Other
User 22	Male	34	PhD	No contact	-	-	Yes	NMMR

User:	Task 1 time (s)	Task 1 # errors	Task 2 time (s)	Task 2 # errors
User 1	53	1	17	0
User 2	89	0	3	0
User 3	111	1	7	0
User 4	115	1	20	0
User 5	156	2	18	0
User 6	45	1	15	0
User 7	112	1	93	1
User 8	124	1	19	0
User 9	58	0	6	0
User 10	174	4	10	0
User 11	79	2	6	0
User 12	138	4	21	0
User 13	105	0	10	0
User 14	65	0	18	0
User 15	203	1	7	0
User 16	119	0	5	0
User 17	81	0	22	0
User 18	80	1	14	0
User 19	107	0	20	0
User 20	70	0	73	4
User 21	71	0	14	0
User 22	47	0	23	2

D

Results

This appendix includes the processing and analysis of the collected data, to get conclusions regarding the applicability and usability of VR in dam health monitoring.

Objective Metrics Results

Time limit (s)	Task 1	200
	Task 2	30

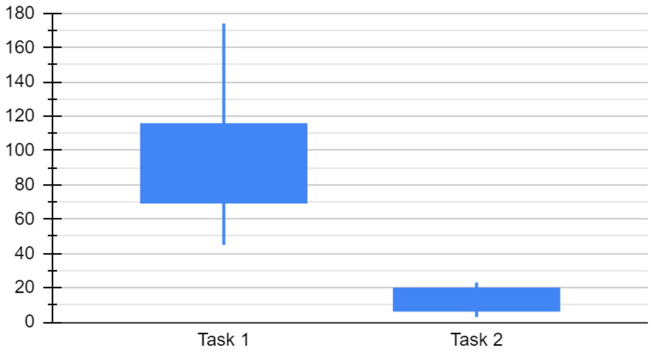
Filtered data			
Task 1		Task 2	
Time (s)	# errors	Time (s)	# errors
53	1	17	0
89	0	3	0
111	1	7	0
115	1	20	0
156	2	18	0
45	1	15	0
112	1	19	0
124	1	6	0
58	0	10	0
174	4	6	0
79	2	21	0
138	4	10	0
105	0	18	0
65	0	7	0
119	0	5	0
81	0	22	0
80	1	14	0
107	0	20	0
70	0	14	0
71	0	23	2
47	0	-	-

		Minimum	Q1	Q3	Maximum
Time (s)	Task 1	45	70	115	174
	Task 2	3	7	19,25	23
# errors	Task 1	0	0	1	4
	Task 2	0	0	0	2

	Count (#)		Percentage (%)	
# errors	0	1+	0	1+
Task 1	10	11	48%	52%
Task 2	19	1	95%	5%
Both tasks	8	11	42%	58%

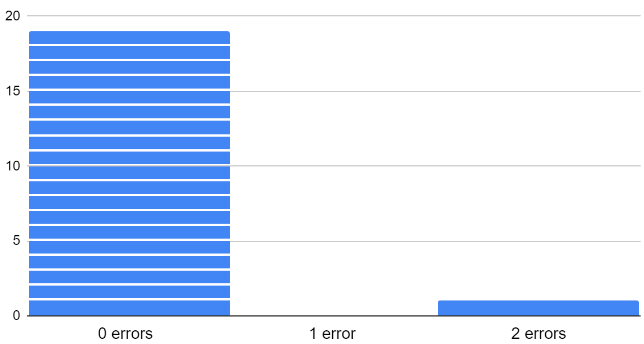
tests < time limit	Count (#)	Percentage (%)
Task 1	21	95%
Task 2	20	91%

Distribution of time required to complete each task



Distribution of the number of errors for Task 1

Distribution of the number of errors for Task 2

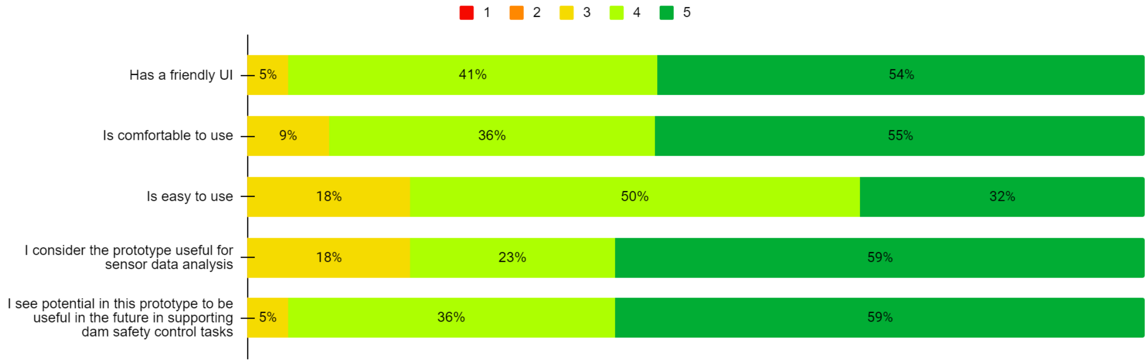


Subjective Metrics Results

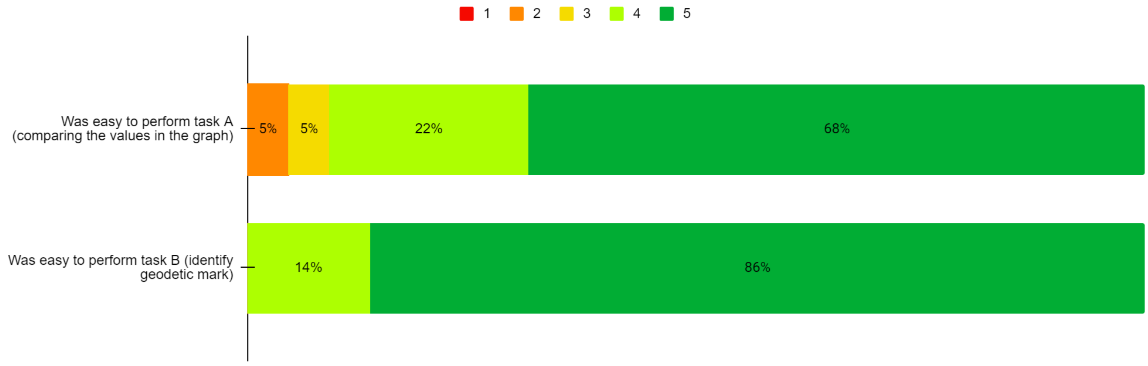
Scale
1 - Totally Disagree
2
3
4
5 - Fully Agree

Regarding the generality of the prototype:	**Q1**	**Median**	**Q3**	**IQR**
Has a friendly UI	4	5	5	1
Is comfortable to use	4	5	5	1
Is easy to use	4	4	5	1
I consider the prototype useful for sensor data analysis	4	5	5	1
I see potential in this prototype to be useful in the future in supporting dam safety control tasks	4	5	5	1
Regarding the tasks:				
Was easy to perform task A (comparing the values in the graph)	4	5	5	1
Was easy to perform task B (identify geodetic mark)	5	5	5	0
Regarding the sensors:				
Is easy to distinguish each type of sensor	4	5	5	1
Is easy to distinguish between different sensors of the same type	4,25	5	5	0,75
Is easy to select each sensor	4	4,5	5	1
Is easy to identify the name/reference of the sensor	4	5	5	1
The sensors have adequate dimensions	5	5	5	0
Regarding the interactive menu:				
Is easy to use	4	5	5	1
Has adequate colors and icons	5	5	5	0
Has adequate dimensions	5	5	5	0
Regarding the data charts:				
The graphs are easy to read	4	5	5	1
Was easy to find the desired information	4,25	5	5	0,75
The colors and dimensions are adequate	5	5	5	0
The data visualization features (approximate/zoom and move/pan) are easy to use	4	5	5	1
Immersiveness and realism:				
The representation of the Cabril Dam is realistic	4	5	5	1
The representation of the area surrounding the dam is realistic	4	5	5	1
I felt immersed in the experience	4	5	5	1

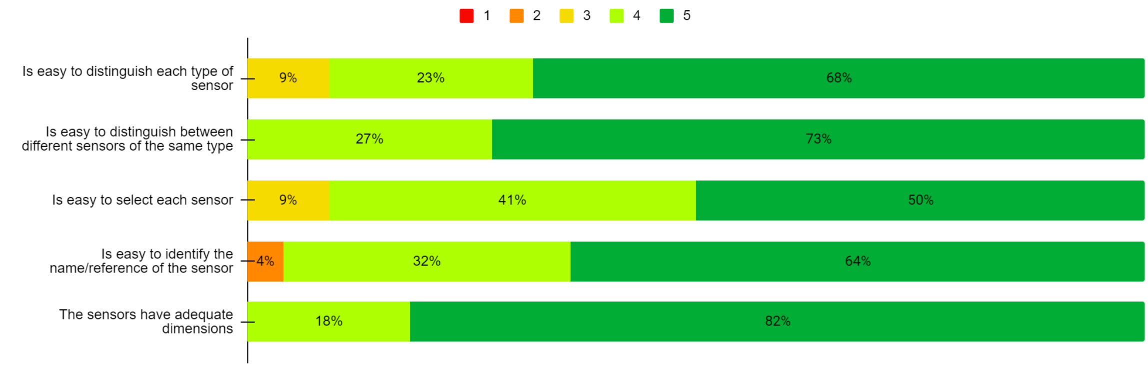
Regarding the generality of the prototype:



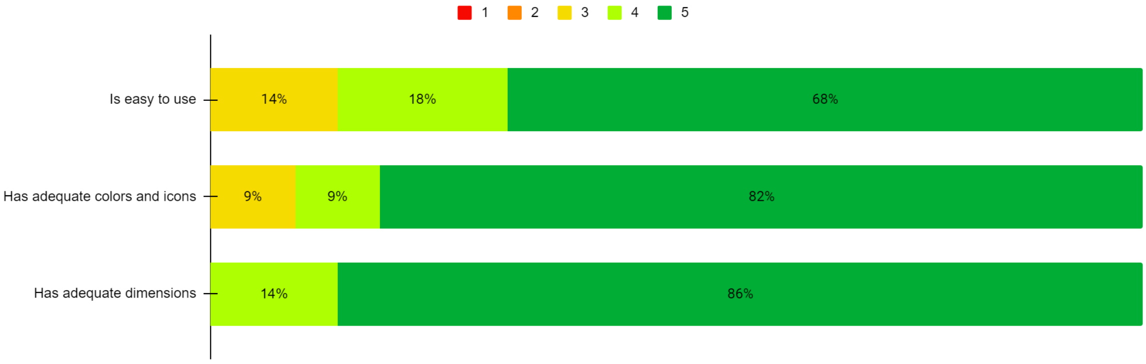
Regarding the tasks:



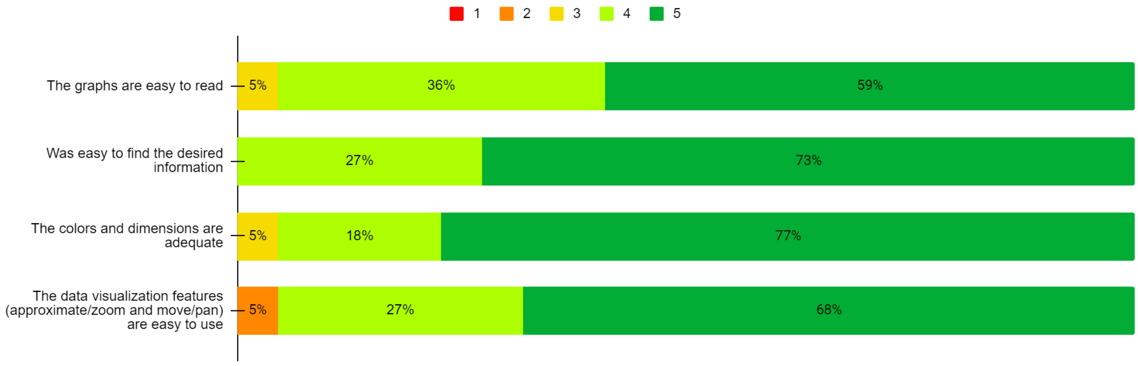
Regarding the sensors:



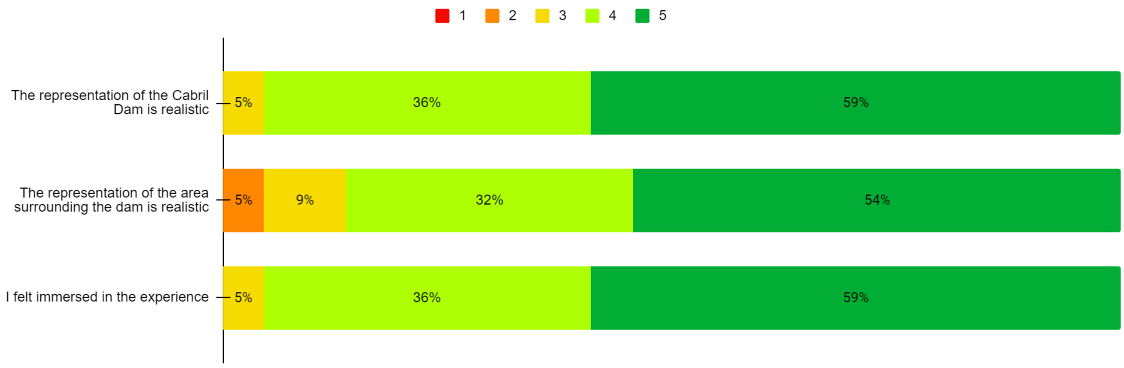
Regarding the interactive menu:



Regarding the data charts:



Immersiveness and realism:



Demographic Results

Gender:		
Male:	Female:	Total:
17	5	22

Age:					
25-	25-34	35-44	45-54	54+	Total:
3	3	6	7	3	22

Education:				
HSDG	Lic.	MSc	PhD	Total:
6	3	1	12	22

Worked in the dam area:		
Yes	No	Total:
19	3	22

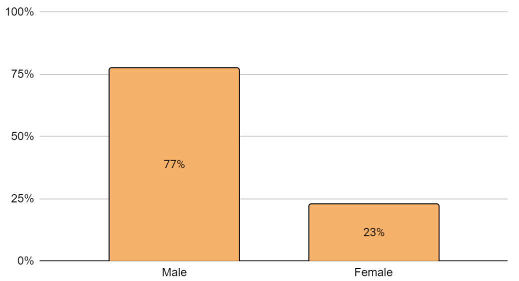
Concrete dams department nucleus:				
NMMR	NGA	NO	Other	Total:
8	5	4	2	19

Contact with VR:		
Previous contact	No contact	Total:
7	15	22

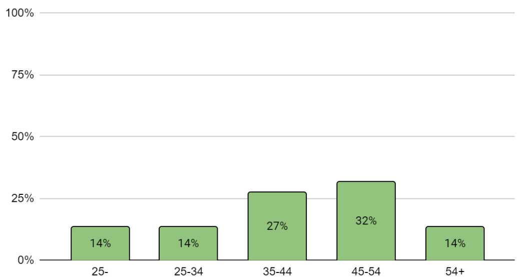
Owned any VR equipment:		
Yes	No	Total:
0	7	7

Used VR in a professional scope:		
Yes	No	Total:
3	4	7

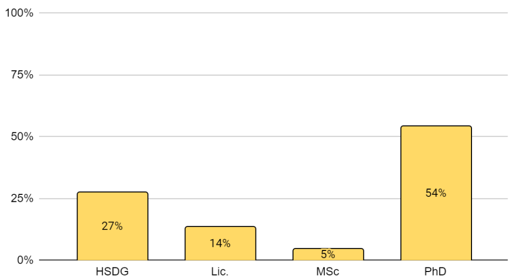
Distribution of participants' gender



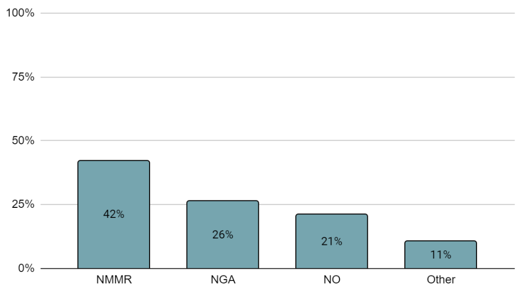
Distribution of participants' age



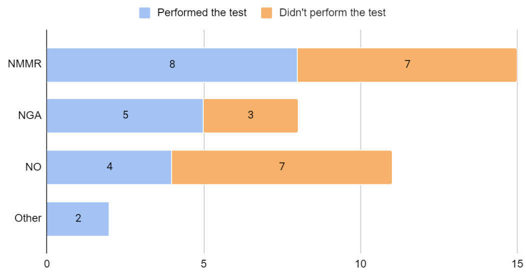
Distribution of participants' education level

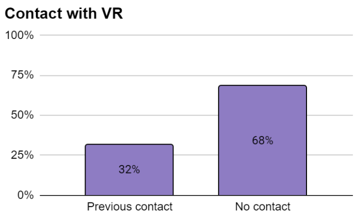


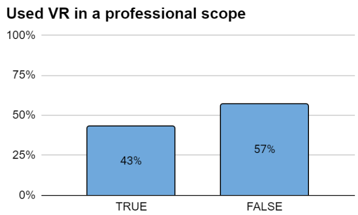
Distribution of participants' investigation unit

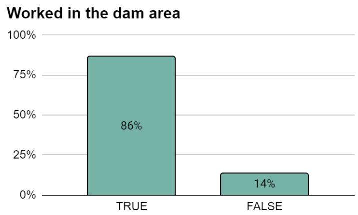


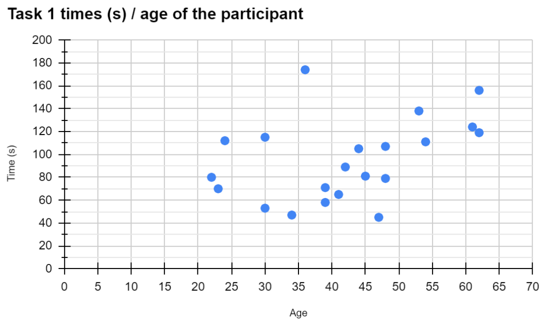
Distribution of the number of participants and non-participants, for each investigation unit

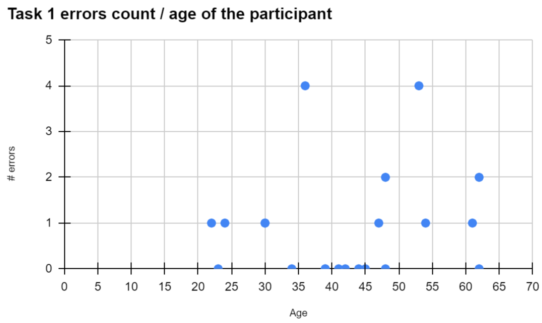


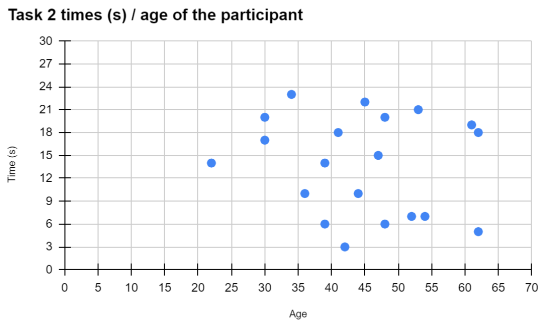

Contact with VR
100%
75%
50%
25%
0%
32%
68%
Previous contact
No contact

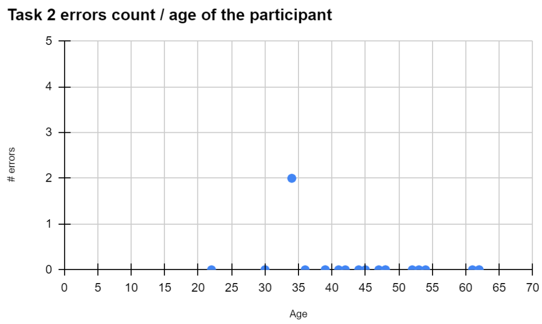

Used VR in a professional scope
100%
75%
50%
25%
0%
43%
57%
TRUE
FALSE

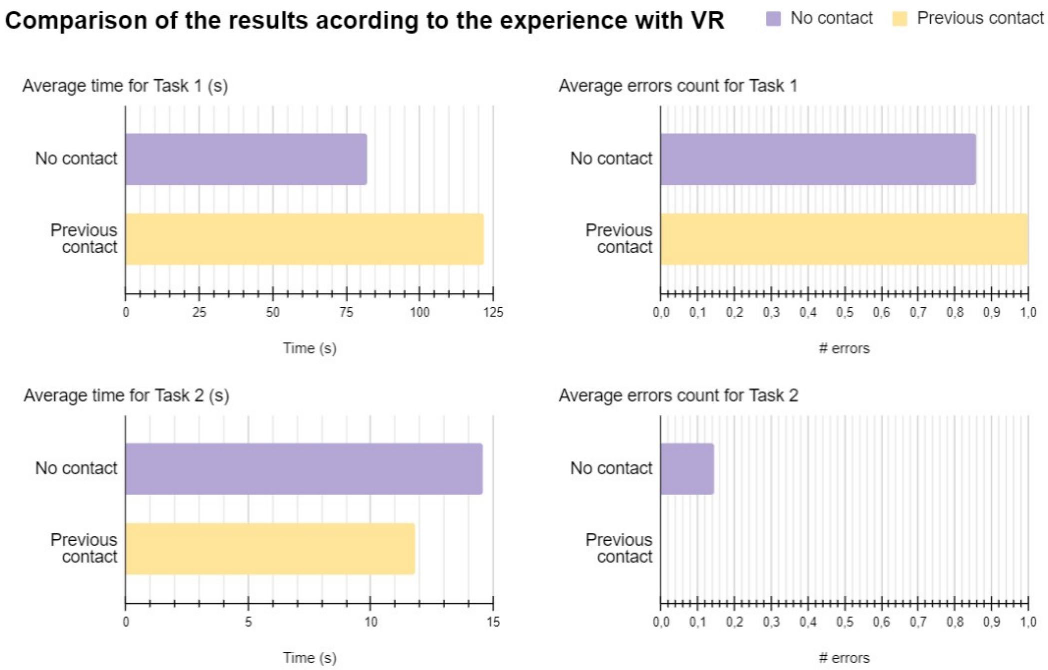

Worked in the dam area
100%
75%
50%
25%
0%
86%
14%
TRUE
FALSE


Task 1 times (s) / age of the participant
Time (s)
Age


Task 1 errors count / age of the participant
errors
Age


Task 2 times (s) / age of the participant
Time (s)
Age


Task 2 errors count / age of the participant
errors
Age


Comparison of the results acording to the experience with VR
No contact
Previous contact
Average time for Task 1 (s)
Time (s)
Average errors count for Task 1
errors
Average time for Task 2 (s)
Time (s)
Average errors count for Task 2
errors

Comparison Between AR and VR

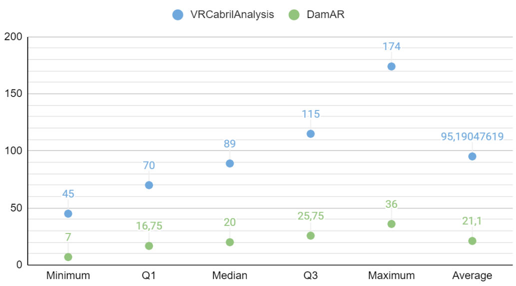
VRCabrilAnalysis																						
Task 1	Time (s)	53	89	111	115	156	45	112	124	58	174	79	138	105	65	119	81	80	107	70	71	47
	# errors	1	0	1	1	2	1	1	1	0	4	2	4	0	0	0	0	1	0	0	0	0
Task 2	Time (s)	17	3	7	20	18	15	19	6	10	6	21	10	18	7	5	22	14	20	14	23	-
	# errors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	-

VRCabrilAnalysis	Minimum	Q1	Median	Q3	Maximum	Average
Task 1	45	70	89	115	174	95,19047619
	0	0	1	1	4	0,9047619048
Task 2	3	7	14,5	19,25	23	13,75
	0	0	0	0	2	0,1

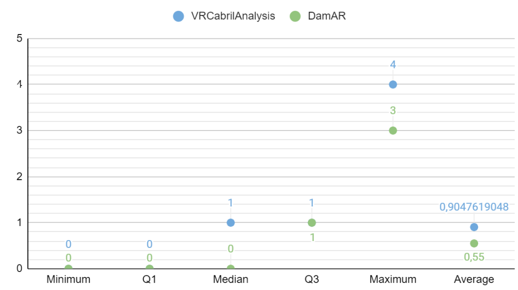
DamAR																					
Task 1	Time (s)	17	35	20	20	13	10	36	17	16	25	28	29	20	17	17	15	21	7	35	24
	# errors	0	3	3	1	0	0	0	0	0	1	0	2	0	0	0	0	1	0	0	0
Task 2	Time (s)	35	22	25	23	13	5	13	21	14	26	17	30	17	15	15	23	10	5	13	10
	# errors	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0

DamAR	Minimum	Q1	Median	Q3	Maximum	Average
Task 1	7	16,75	20	25,75	36	21,1
	0	0	0	1	3	0,55
Task 2	5	13	16	23	35	17,6
	0	0	0	0	1	0,2

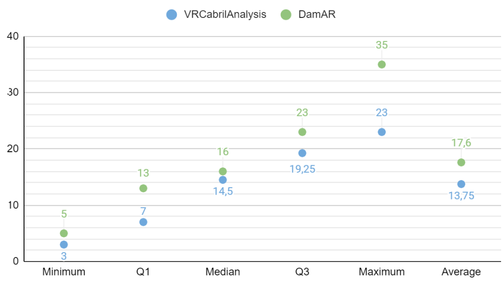
Task 1 Time (s)



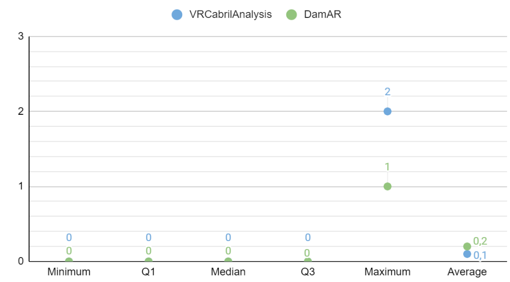
Task 1 # errors



Task 2 Time (s)



Task 2 # errors



Levene test			%	> 5%?	Variance
Task 1	Time (s)	0,00000002588738046	2,59E-06	FALSE	Unequal
	# errors	0,3858533076	3,86E+01	TRUE	Equal
Task 2	Time (s)	0,3777500829	3,78E+01	TRUE	Equal
	# errors	0,7118136961	7,12E+01	TRUE	Equal

Unpaired *t-test*			%	> 5%?	Significant difference
Task 1	Time (s)	0,000000003949524208	3,95E-07	FALSE	TRUE
	# errors	0,3161348022	3,16E+01	TRUE	FALSE
Task 2	Time (s)	0,1004097896	1,00E+01	TRUE	FALSE
	# errors	0,4657758419	4,66E+01	TRUE	FALSE