Immersive Analytics for Dam Analysis

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

With the development of new technologies, virtual reality has been gaining prominence and relevance in various fields. Our work aims to gauge whether using such technologies can improve the complex process and tasks of dam monitoring and inspection. As a first approach, we propose developing a virtual reality application that provides an immersive representation of the Cabril Dam landscape. This innovative application aims to facilitate the day-to-day work of dam engineers and technicians, allowing them to visualize critical data, including sensors, computed and observed displacements, and differents modes of vibration of the Cabril Dam, while being able to interact with it in revolutionary ways that were previously not feasible. To validate our investigation and the potential of our prototype in the dam domain, we carried out user test evaluations, from which we gathered conclusions that are promising for the future of these technologies in dam inspection and monitoring.

Keywords

extended reality, dam monitoring and inspection, immersive analytics, structural health monitoring

Resumo

Com o desenvolvimento de novas tecnologias, a realidade estendida começou a ganhar uma relevância significativa em vários campos. O nosso trabalho explora a aplicabilidade destas tecnologias ao complexo processo e tarefas de monitorização e inspeção de barragens. Como primeira abordagem, propomos o desenvolvimento de uma aplicação de realidade virtual que fornece uma representação imersiva da paisagem da Barragem de Cabril. Esta aplicação inovadora visa capacitar os Engenheiros e Técnicos de barragens, permitindo-lhes visualizar dados críticos, incluindo deslocamento e diferentes modos de vibração, tudo isto enquanto podem interagir com ele de formas revolucionárias que anteriormente eram impossíveis. Para validar a nossa investigação e o potencial das referidas tecnologias no domínio das barragens, realizámos avaliações de teste com utilizadores, cujos resultados oferecem perspectivas promissoras para o futuro da inspeção e monitorização de barragens.

Palavras Chave

realidade estendida, monitorização e inspeção de barragens, análise imersiva de dados, monitorização da saúde estrutural

Contents

List of Figures

List of Tables

1

Introduction

Over the past few years, data visualization has been gaining a strong interest, because of its capabilities in increasing value and through innovative ways of displaying information. Virtual reality with its multitude of possible uses, stands on the verge of deep changes in the way we blend the real and the virtual.

Immersive Analytics stands at the intersection of recent technological advances, by offering a new and enriched way to understand and interpret data. Instead of only relying on numerical evaluations, it creates a new path in interacting with the data, diverging from the current approach. Fully utilizing virtual reality devices to their potential, data can be explored deeper than before, placing a higher focus on decision-making and analytical reasoning. This approach will transform user interaction and visualization - bringing new fully immersive environments, and unlocking the potential and novel perspectives in data analysis. With immersive analytics, we are set to go into unexplored territories in the realms of data comprehension and interaction.

The Fourth Industrial Revolution, often named Industry 4.0, has been gaining significant momentum in this century, driven by the latest technological advancements and enhancements. It highlights just how important the modern shifts in automation are, where connectivity tends to prevail, fostering new production methods, value creation, and optimization techniques. This evolution introduces new concepts such as the digital shadow and digital twin. Furthermore, as we keep crossing the borders between the physical and the digital world, Immersive Analytics emerges as a pivotal tool. It allows domain experts who often need to make decisions to immerse themselves in a data-rich environment where they can extrapolate insights and relevant information, harnessing the power of Industry 4.0. In this new industrial era, these visual and interactive platforms are key to getting the full potential out of the businesses' data.

In this new innovative era, we arrived at Construction 4.0, which still remains more theoretical than tangible, it's viewed as a process that allows us to integrate new technological strategies within the current construction realm. The primary goal of Construction 4.0 is to use and leverage the new technologies and replace the human position in making the association between the construction sites and their associated models.

A digital twin can be compared to a backup of data and infrastructure, it's an incredible new way to virtually represent a physical object or infrastructure. This allows us to evaluate problems within our data with much higher precision and even to transmit data into the infrastructure since the digital twin implements a two-way data transmission. Within Construction 4.0, digital twins are changing the ways things are done by offering virtual replicas of structures, which will enable professionals to predict their issues and models, streamline workflows, and improve the project's efficiency and efficacy.

In contrast to the digital twin, the digital shadow only has one-way data transmission, it isn't capable of transmitting back insights to the infrastructure. A digital shadow emerges as a virtual copy to interact with people and environments. In other words, a digital shadow may be created from a digital twin to capture and simplify the enormous amount of data that passes through a digital twin. While we would like to be able to take leverage of Immersive Analytics and develop a tool that could be a digital twin of the Cabril Dam, in this work, we sought to be a first step in that path, by developing a digital shadow of the dam to be used by dam domain experts.

1.1 Motivation

In 2015, the United Nations developed a plan called the 2030 Agenda for Sustainable Development which is a list of seventeen areas in which humanity should focus in order for the world to keep growing in a sustainable way, "a list of things to be done in the name of the man and the planet". The aim of this work is directly involved with goals set on Objective 7: Accessible and Renewable Energies since we will be aiming to develop a tool that will help in the monitoring of dams and, therefore, will aim to increase our energy efficiency but also provide a way for in developing countries to modernize their technology and infrastructure used for the production of energy.

Furthermore, our efforts align with Objective 12: Sustainable Production and Consumption. Through vigilant dam monitoring, we aim to optimize the management of the natural resources within the dam, promoting more sustainable use and consumption.

Today, dam engineers and technicians are still relying on conventional methods for data visualization. With the advancements in technology, we believe that we can incorporate these emerging technologies and facilitate the daily tasks often done in the domain of dam monitoring and inspection, these traditional techniques, despite being useful, pose significant constraints on visualization capabilities and the depth of information they can derive from the dam.

1.2 Objectives

In this work, we will investigate and explore whether these new emerging technologies could be of use in dam monitoring and inspection. We intend to create a first prototype, making use of virtual reality, where dam engineers and technicians can derive information in an immersive environment.

Utilizing virtual reality, we aim to develop an application designed for visualizing and interacting with the extensive data derived from the sensors present at the Cabril Dam. The integration of multi-sensory interfaces, which tend to promote collaboration, seeks to enable users to visualize this data in a three-dimensional environment, superimposing the Cabril Dam landscape. Moreover, the capacity of virtual reality for in-situ visualization stands out as one of its most revolutionary features. Users won't just observe data in real-time; they will also experience a sense of presence within the dam landscape, enhancing their overall engagement and understanding.

Immersive Analytics offers distinct advantages over traditional data methods. By enabling three-dimensional interactions, it promotes the comprehension of complex datasets with a higher degree of certainty, which can potentially highlight aspects missed in 2D representations. Furthermore, the immersive environment can suit varied learning styles, which is incredibly important in a diverse world, fostering a more inclusive data interpretation. As we progress, our work will determine the extent to which these modern techniques can outpace conventional methods.

A collaborative work environment is fundamental to our work. It not only improves the collective problem-solving but also agilizes the resolution. Moreover, with team members being able to be located at different locations - from LNEC offices to on-site at the dam or even at EDP - this collaborative environment ensures seamless integration of these new technologies. Such synergy not only facilitates mutual learning but also adds significant value to our collective endeavors.

While creating a digital twin of the dam would be the scope of a final prototype, this project intends to be an initial step toward the eventual implementation of a digital twin in the future. Our tool is designed to serve as a digital shadow of the Cabril Dam, aiming to generate a virtual replica of the dam landscape that allows for interaction and immersive engagement with its data, which is crucial for effective dam monitoring and inspection.

In conclusion, the objective of this work is to simplify and further facilitate the day-to-day tasks of technicians and engineers engaged in the monitoring and inspection of the Cabril Dam. By leveraging these technologies and exploration, we aspire not only to facilitate their tasks but also to introduce innovations that seek to elevate the standards of dam monitoring and inspection.

2

Background

A brief introduction to the concepts regarding structural health monitoring and dam monitoring, both these topics are key to understanding the goals developed in this work. With this in mind, it's also important to investigate the evolution of extended reality in recent times and the characteristics of immersive analytics.

2.1 Dam Monitoring

As the significance of dams in water management, and energy production, for the needed energetic transition, the necessity for rigorous dam monitoring and inspection has grown over time. Ensuring the safety, efficiency, and correct operation of these large civil engineering structures requires comprehensive observation methodologies and cutting-edge technologies. This section goes into the complexities faced in dam monitoring, highlighting its importance, the challenges faced, and the innovative techniques employed by dam engineers and technicians. By shedding light on the multifaceted aspects of monitoring, we underscore the complex collaboration needed between engineering, environmental considerations, and safety norms in the realm of dam monitoring.

2.1.1 Structural Health Monitoring

Structural health monitoring (SHM) represents a critical aspect used in civil and structural engineering, and it aims to ensure the integrity, safety, and longevity of built infrastructures. By utilizing advanced sensors, data analysis, and state-of-the-art diagnostic tools, SHM provides real-time insights into the condition and performance of structures, ranging from bridges and dams to other important civil engineering structures. This proactive approach helps in the early detection of potential problems or damages with the structure but also assists in optimizing the maintenance schedules of said infrastructures, enhancing their lifespan, and ensuring safety procedures. As urbanization progresses and the demands on infrastructures increase, the role of structural health monitoring becomes even more important to society as a whole.

The importance of SHM cannot be overstated in the modern management of infrastructures. By proactively identifying and reducing potential weaknesses and flaws, it plays a crucial role in ensuring safety and longevity. From an economic point of view, the initial costs of implementing SHM are dwarfed by the potential financial consequences of system failures or severe damages, which highlights its value as a key preventive measure in engineering practices.

In today's engineering world, SHM systems try to incorporate the latest technological innovations and structural safety. Utilizing an array of sensors, wireless communication methods, and sophisticated data visualization and analysis, these systems constantly collect and analyze data to gauge a structure's health in real-time, accessible from remote methods. These can come from subtle shifts in building foundations or tracking temperature variations in critical infrastructures, modern SHM tools provide invaluable real-time information, facilitate prompt maintenance, and allow for immediate corrections if needed.

2.1.2 Cabril Dam

The Cabril Dam, located on the Zezere River in central Portugal, right on the edges of the counties of Pedrogrão Grande and Sertã, is a testament to engineering and sustainable energy solutions. This concrete double-curvature arch dam plays a pivotal role in the nation's energy supply and utilizes the river's flow for hydroelectric power generation since it has a hydroelectric power plant in its downstream base. Beyond its primary purpose, the dam's reservoir ranks among Portugal's largest artificial lakes. While it supports the hydroelectric mission of the dam, it also serves as a vital water reserve for the region. The Cabril Dam (Fig 2.1) stands as an important landmark, reflecting Portugal's commitment to the sustainability of resources and energy transition.

The Cabril Dam observation system monitors a range of different factors to ensure its structural integrity and optimal operation. These include the water level in the reservoir, vertical and horizontal displacements in the structure and in the foundation, relative movement in joints and cracks, air

Figure 2.1: Cabril Dam

temperature, concrete temperature, foundation temperature, concrete extensions, subpressions in the foundation, drained and infiltrated flows, and dynamic accelerations.

The dam's observation system improves its overall safety and effectiveness by constantly monitoring these elements which are later assessed to help in making a decision to detect potential problems, giving dam technicians more time to act and prevent them. This system provides stability and longer longevity for the dam and all of its structures while allowing the Cabril Dam to remain compliant with all the safety measures and regulations, and legal requirements.

The water levels in the reservoir and downstream are automatically measured by limnimeters and visually through limnimetric scales. A meteorological station is also installed in the dam. This station has a maximum and minimum thermometer, a simple thermometer, and a hygrograph for measuring and recording temperature and ambient humidity. To complement the control of the environmental conditions to which the dam is subject, a thermometric probe and an udometer are installed that integrates the automatic data collection system.

At the Cabril Dam, the monitoring of displacement is either done by geodetic methods (Fig 2.2), by using plumb lines or by using extensometers. In the case of geodetic marks, they are monitored using fixed devices placed in the downstream area of the dam. The plumb lines are only capable of assessing the horizontal displacements and in total, there are ten currently installed in the structure.

On the contrary, extensometers are only capable of measuring vertical displacements in the foundation, with nine of them installed at the dam, and with the exception of two, all of them are installed in vertical holes.

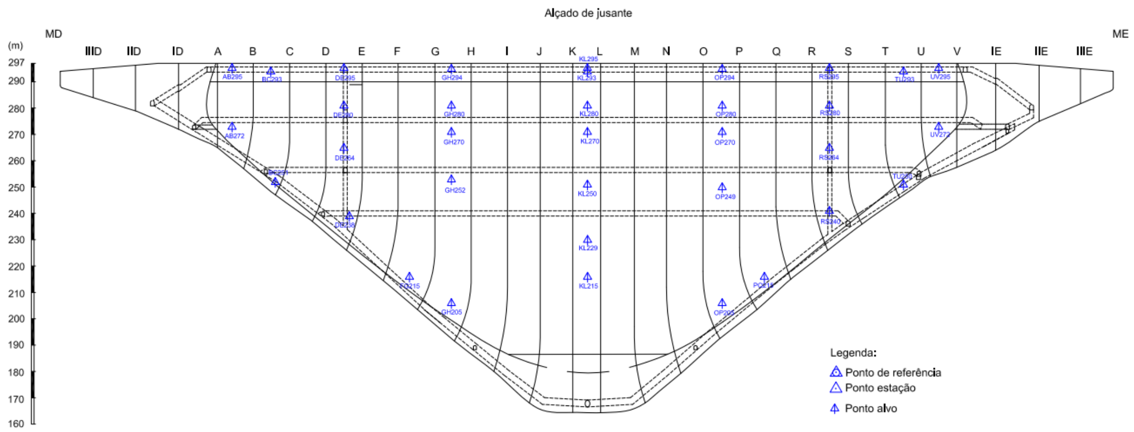


Figure 2.2: Location of the Geodetic Marks [1]

Relative movements in joints and cracks are measured through Carlson-type electrical resistance joint motion meters embedded in the concrete and through extensometer bases, in the accessible areas of the work, with a total of one hundred and twenty-eight installed at the dam.

The observation system is composed, also, of thermoelectric pairs that were later complemented by electrical resistance thermometers to help in the assessment of the temperature of the concrete. This monitoring is done in reading stations distributed along the dam's galleries. Beyond the temperature, the extensions of the concrete are also monitored and for that, a group of one hundred and seventy-five Carlson-type electrical resistance strain gauges is currently in use, which can be placed isolated or in groups.

The outflows are measured individually at the outlets of the drainage holes and in five taps, which collect the drained and infiltrated outflows. These taps allow the reading of the accumulated outflows by zones, namely the right bank slope, the left bank slope, the right valley bottom, and the left valley bottom. To ensure accurate measurements, it is essential to consider the various factors that can affect outflows. Additionally, by measuring outflows in five taps, it is possible to calculate the amount of water collected and infiltrated in each area. This provides a more comprehensive understanding of the outflows in an area, which can be used for a variety of applications.

The Cabril Dam is equipped with three triaxial accelerometers (Fig 2.3) and sixteen uniaxial accelerometers that work together to provide a continuous monitoring system for the dynamic behavior of the dam. The uniaxial accelerometers are placed at a different quota and spaced 20 meters apart from each other to measure radial accelerations inside the dam. The values collected from the accelerometers are stored at an hourly rate inside the local server located at the observer's office, with all this data being continuously transmitted using a fiber optic network from which all the accelerometers are connected along with electrical signal acquisition and digitization units and data concentrators.

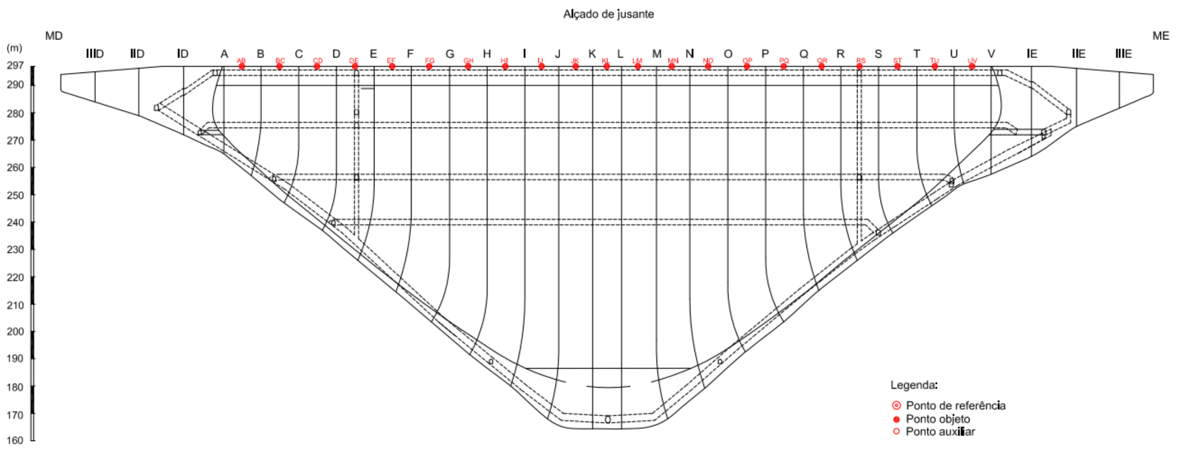


Figure 2.3: Location of the Triaxial accelerometers [1]

Figure 2.4: GNSS receiver and its location. [2]

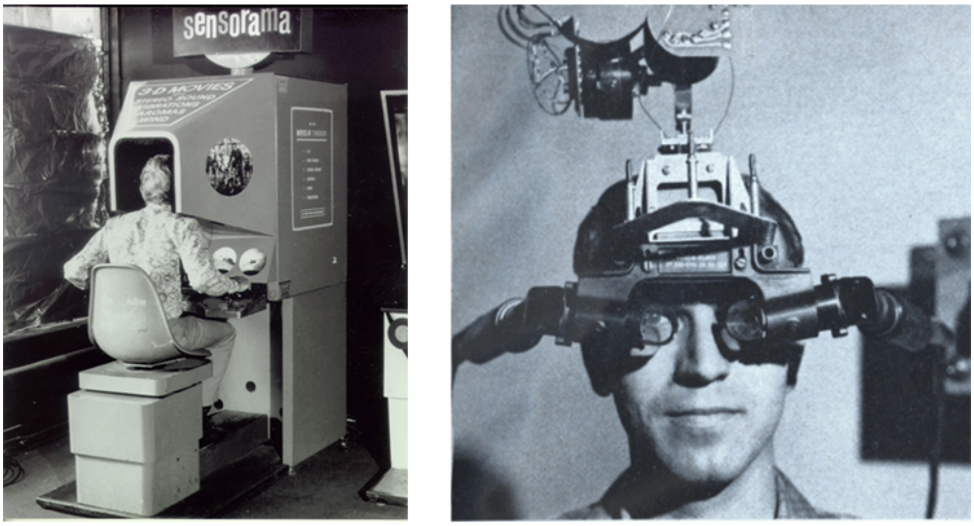
The Cabril Dam has faced cracking issues since its initial filling, which underscores the significance of precise and continuous displacement monitoring to better monitor these kinds of problems. Especially crucial is the monitoring of several notable points, one of which is the point at the top of the central section of the dam where no plumblines are mounted. To address this, a GNSS antenna (Fig 2.4) has been implemented to capture displacements at this critical location. This implementation showcases the potential of GNSS in providing real-time data for vital structural points, allowing for the dam inspection to be done faster so that it secures the operation of the dam.

2.2 Virtual Reality

In the constantly evolving world of technological innovation, virtual reality has emerged as one of the most revolutionary domains, redefining and contributing to a new human interaction with the digital and physical worlds. This section digs into the realm of VR. We'll explore its evolution through history, current applications, and its corresponding areas, and the potential it holds for reshaping the world, from entertainment and education to healthcare and engineering. As we go through this segment, the pivotal role of VR in bridging the physical world and the digital world sets the stage for a future where our perception of reality is expansively enriched.

2.2.1 Evolution of VR

Virtual reality (VR) has witnessed a radical evolution over the last few years. Its origins go back to the early experiments of the 1960s, such as Morton Heilig's Sensorama and Ivan Sutherland's "Sword of Damocles" (Fig 2.5), which continuously introduced the foundational concepts for immersive environments. By the 1990s, VR was a foothold in popular culture, although the technology of the time still had limitations in areas such as graphics, interactivity, and user experience.



(a) Sensorama (b) Sword of Damocles

Figure 2.5: XR Experiment in the 1960's

Into the 21st century, advancements in technology, such as bigger computational power, better graphics rendering, and even sensor tech created a revolution in VR. Companies like Oculus and HTC brought high-end VR into the consumer market. These developments, aided by more intuitive user interfaces, improved haptic feedback, and AI integration, have transformed VR from a niche interest into a dominant force in many industries that go from entertainment to engineering.

As we take a look towards the future, VR continues to blur the lines between the digital and physical realms, promising to not only enhance the experience and sensations but a complete redefinition of the interactions between humans and technology and the world.

2.2.2 Current Applications of VR

As industries evolve in the digital age, a revolutionary shift is being observed in how we interact with our surroundings and with technology. More and more innovative platforms are offering immersive experiences that seek to bridge our physical world with computer-generated realities. Within healthcare and education, this revolution has enabled unparalleled advancements and achievements. Surgeons are now capable of overlaying critical data during procedures such as surgeries to enhance precision (Fig 2.6), while educators are breaking the confines of classrooms, transporting students into experimental learning environments that range from ancient civilizations to the vastness of space, which creates an unparalleled sense of presence.

Focusing solely on construction and engineering, the influence of these virtual realities is remarkable. Architects visualize complex structures on real-world sites through digital overlays, superimposing and resolving design challenges in a timely manner. Engineers, on the other hand, can now simulate machinery operations and safety tests in a risk-free virtual space, to prepare for the real-world execution of these procedures. These tools are not only enhancing efficiency and safety but are also revolutionizing safety methods and resource management.

Figure 2.6: Current VR Applications

Transitioning to entertainment, this paradigm shift is creating environments where narratives are no longer defined by the size of the screen. Games are inviting players into expansive, interactive realms where everyone can collaborate, while movies are offering enveloping experiences, reshaping the very essence of storytelling. As these immersive technologies become more common in our day-to-day routine, they promise a future where our interactions, will be completely revolutionized, deeply enriched, and expansively engaging.

2.2.3 Challenges

The promise of Virtual Reality is vast, opening various new doors to immersive experiences and closing the gap between the physical and digital worlds. Yet, this path to seamless integration is filled with an always-growing list of challenges. One of the primary problems is the technical limitations that current hardware still presents. Devices have a need to be lightweight and comfortable for long-term usage, but they also must contain enough computation power and graphics rendering for a smooth experience. Balancing these requirements often leads to compromises, either in the form of reduced immersion or the inconvenience of an uncomfortable device.

Another significant challenge that VR faces is the development of intuitive user interfaces and interactions in the virtual space. Traditional methods of interaction, like clicks or gestures, do not always translate as supposed into a 3D environment. Designers and developers are constantly trying and create new interaction methods that feel natural, intuitive, and closer to reality. Additionally, some issues related to motion sickness, accessibility for those with disabilities, and ensuring safety in physical spaces while users are immersed in virtual ones are still ongoing concerns despite enormous advancements in the last few years. As virtual reality continues to evolve, revolutionizing the world, addressing these challenges is crucial to unlock its full potential.

2.3 Immersive Analytics

2.3.1 Evolution of Data Visualization and Interaction

The beginnings of data visualization can be traced to ancient civilizations that utilized rudimentary maps and graphs for data representation. As history progressed to the advent of computers at the end of the 20th century, digital graphs and charts began to appear on screens all over the world, developing in an era where users could interact with and extrapolate information from data in unprecedented ways never seen before. This digital evolution emphasized the importance of simplicity, aesthetics, and interactivity in data visualization.

However, as the 21st century came around, the digital revolution gave birth to what we now know as big data. With an impressive increase in the volume, velocity, and variety of data being generated, traditional 2D, desktop-based visualizations found themselves to be too overwhelming and often inadequate for most users to properly interpret them. The task at hand was not just to display large quantities of data, but to make it clear and interactive. The demand for more complex visual representation created innovations in display technology and a push for more interactive and immersive dashboards that could provide users with a sense of immersion within the data.

In order to face the challenges of this data-heavy era, immersive analytics emerged as the logical step. Leveraging the potential of technologies such as augmented and virtual reality, this approach took users and placed them at the center of data-moved virtual environments (Fig 2.7). Users went from being passive observers to active participants in a collaborative environment, capable of navigating and interacting with expansive 3D data realities. This shift from traditional screens to more complex, immersive data worlds evidences the monumental steps data visualization has taken, positioning immersive analytics at the pinnacle of data interpretation in our digital world.

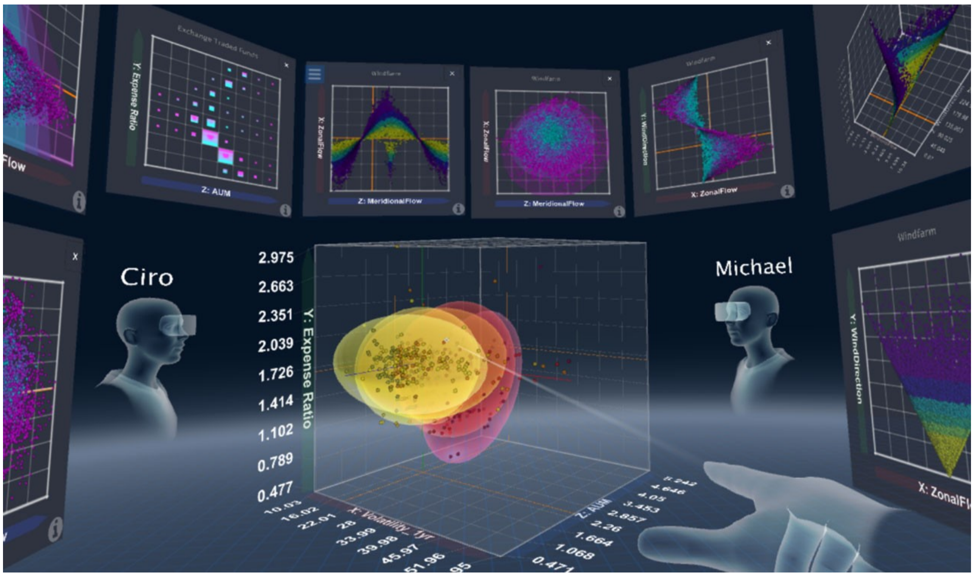


Figure 2.7: Example of an Immersive Analytics application

2.3.2 Human Perception, Cognition, and Immersive Environments

Human perception and cognition form the stepping stone upon which any immersive experience is built. Our sensory systems – such as vision, audition, and touch – function to process information from our environment, and construct a vision of reality that our minds perceive. As XR interfaces are designed, they need to understand these fundamental processes. For instance, if a virtual environment doesn't respect the way our brain gauges its surroundings or spatial relationships, it can create disorientation or even cause motion sickness, which demonstrates the importance noted on these key aspects.

Moreover, XR environments will always offer unique challenges and opportunities concerning our cognition. Immersive environments can go into our spatial memory capabilities and surroundings, allowing for a more intuitive data organization and recall. However, these technologies also need to factor in for potential cognitive overloads. In a densely packed XR scenario, users can become overwhelmed, leading to reduced information retention or even aversion to the technology. Being able to offer rich immersive experiences without the possibility of overbearing the users is a primary concern for XR design.

Finally, these concerns extend beyond just the individual user. Social cognition – understanding and reacting to collaborative interactions – also plays a key role in XR. Virtual meetings or collaborative platforms in XR environments are more than just about transmitting data. They must allow for nuances like eye contact, and facial expressions, as these are fundamental to how the user will communicate and interact. As XR technology keeps evolving, its intersection with the dimensions of human perception and cognition will remain at its core, being one of the factors to evaluate its growth and ensure its adaptation to our fundamental operations.

3

Related Work

Ever since virtual reality started becoming more accessible and more common, areas such as the AEC have been looking for ways to use it, whether it is to perform structure health monitoring of certain infrastructures or to better retrieve insights due to its projections capabilities.

Due to the possibility of prototyping on a model of the infrastructure, instead of a physical model or even on-site, VR can be useful because it gives a clearer idea of the solution that we are trying to develop.

3.1 Traditional Approaches regarding Data Visualization of Dams

To reduce the number of fatalities of construction workers working in large water infrastructures such as dams, Peng Lin [10] developed a real-time monitoring system that aspires to use automatic detection and intelligent tracking systems to get instant control feedback information and, therefore, able to know in real-time when said workers are entering certain dangerous zones and provide an analysis of their work behavior. This tool is useful for acquiring knowledge in order to support the decision making when evaluating a worker's behavior in real-time since not only does it help in getting a better grasp of how the worker performs and which paths he takes but can also be useful to analyze what happened in an emergency situation due to its capability of allowing users to call for said situations.

Zhang [3] (Fig 3.1) researched the possibility of developing a tool to enable remote consultation about dams in places where it is not realistic to call an expert, like remote areas, whenever an unexpected situation arises. Currently, most dam consultation systems only make use of advanced video communication systems, and a simple remote video conference but the author proposes a tool that provides visual information query along with information analysis, structural analysis, and other functions to realize an intelligent remote consulting of dams.

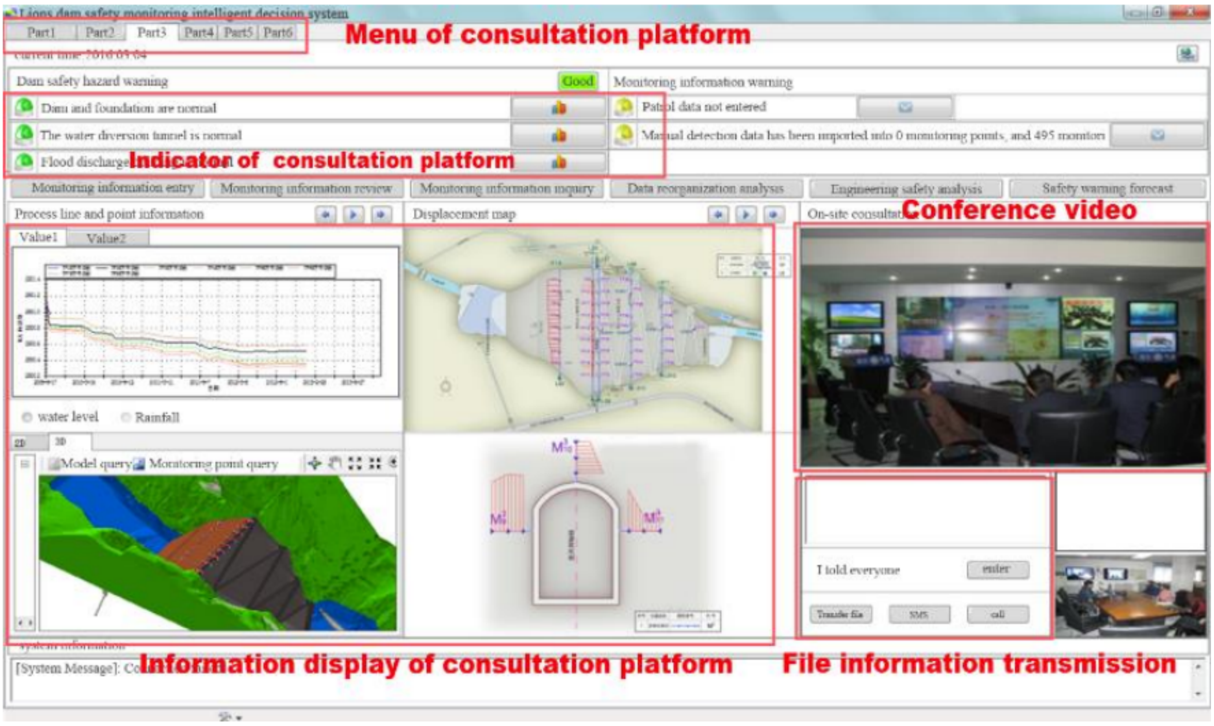


Figure 3.1: Proposed Dam Consultation System by Zhang [3]

The system has successfully been applied to a real dam, the Shiziping Hydropower Station, allowing domain experts to retrieve information, and do a real-time safety analysis and decision-making simulation through remote methods. Not only that but the platform has a reasonable structure that allows easy remote meetings and collaboration between domain experts while analyzing the dam itself.

At the beginning of the millennium, the systems used to monitor dams were based on limited applications and old-dated technologies, and with a big number of deficiencies regarding its control of quality, usability, and maintainability, so Alberto et al. [11] developed a tool called GestBarragens that after an initial study, identified the most important aspects in which their solution must focus. This tool is needed to allow users to observe the physical measures obtained from the dam, it should support the behavior model of each dam, should track the process of visual inspection that is done periodically in person, and finally, the process of management and consultation of support information and documentation along with a system to make a decision whenever an anomaly is registered in the operation of the dam. Gest-Barragens is accessible via a web portal and it presented innovative mechanisms regarding the analysis of information about dams, also allowing compatibility with reading and synchronization mobile devices.

3.2 VR/AR Use Cases in Architecture, Engineering, and Construction

The construction industry has been since forever one of the industries most plagued with worker injuries and fatality, to improve it in these terms Mehdi Hafsia [12] developed a virtual reality simulator that intends to reduce these risks by allowing workers to train in a risk-free environment and raise their awareness of health and safety. This application has been developed to train workers in the specific case of dealing with a formwork panel in which they are instructed first to complete all the security steps first which includes putting on the helmet and the anti-noise headphones to lastly, working on a virtual model of a formwork. If the worker does something that may put him in danger in the real world, the application will immediately inform him.

To address the fact that most AEC, architecture, engineering, and construction students should get some kind of collaboration work experience before graduating, Tzong-Hann Wu [4] developed a tool that aims to allow them to cooperate in global projects using a virtual reality system which is, nowadays, almost a requirement for every engineer in order to get better problem-solving skills (Fig 3.2). The solution is an avatar-based communication platform where you can switch between a normal virtual reality world or a more immersive approach. In both approaches, students will collaborate with orders and can see the effects of their actions in real-time which increases their sense of teamwork along with their problem-identifying and solving skills. Not only that but this way, they are also warned about the safety measures that one should know in a real-world environment along with providing feedback instantaneously and in a clearly visible way.

Oluseyi Julius Adebowale [13] studied how augmented reality can be applied to improve productivity in a construction environment and why these technologies are seen as key in the future of construction. This work showed that various areas will have improved productivity, such as component assembling due to AR's capability of overlaying data information on construction sites, or planning since a project manager can gather information about what's built and what's planned with ease and display it instantly, or just to decrease the difficulty to get knowledge about the project by using a virtual model of the construction scene from which everyone can grasp a better viewing. The only things that are currently preventing this productivity environment are that the cost of Augmented Reality could still play a factor for some construction companies and the fact that some construction companies may lack functional

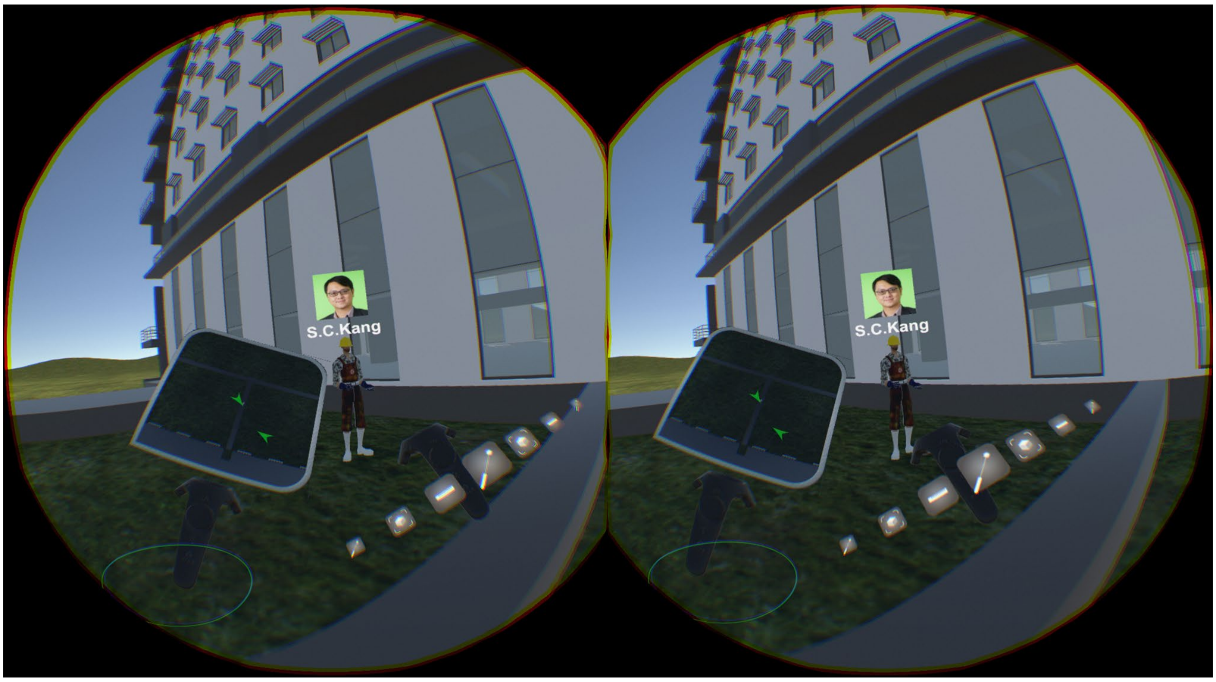


Figure 3.2: Remote collaboration to improve safety by Tzong-Hann Wu [4]

information technology departments.

Regarding urban landscape design, Xiang Li [14] studied the possible uses of virtual reality during the process of designing a landscape in real-time. Problems such as the interactivity, the immersion feeling, and the independence of the objects when landscaping using traditional methods can be reduced when immersing in a virtual reality environment. This solution allows designers to visualize a three-dimensional model of the designed landscape in real-time, allowing them to also act faster in the process of finding and solving problems which increase the effectiveness of their work. Not only that but the designer will also be able to change the conditions in the environment, like the weather or the feeling of the green space which allows them a higher level of perception.

To improve the renovation of buildings, Alessandro Carbonari [15] developed a platform that uses MR and is devoted to improving the efficiency of building renovation design. This platform is constituted by a web application and an NFC scanning device so that users can easily align their virtual objects and then superimpose them over the existing building that they want to renovate. This application simplifies the process of designing and comparing the different types of renovation possible in each infrastructure. This platform can also improve the on-site assessment of a building renovation design with the only requirement being that designers must work in a BIM environment so that it's possible to convert the renovation models to a suitable MR model and so that the experts can visualize on-site models and give their input in an asynchronous way.

On the planning of large water infrastructures such as dams, Alessandro Ros [5] developed a tool with two visualization modes, between AR and VR that can be used to aid in the planning and building of concrete gravity dams (Fig 3.3). This solution allows the designer to easily visualize and prototype the dimensions and architecture of the dam itself, not only that but it's also useful due to its capabilities to have different versions of the same project where the designer can test different solutions even using the landscape where the dam is intended to be built. This solution also aims to replace, or at least, diminish the need for physical meetings that may involve people from all around the world with its networking capabilities that allow for remote collaboration while planning for the construction of dams, therefore, saving money and reducing the carbon footprint.

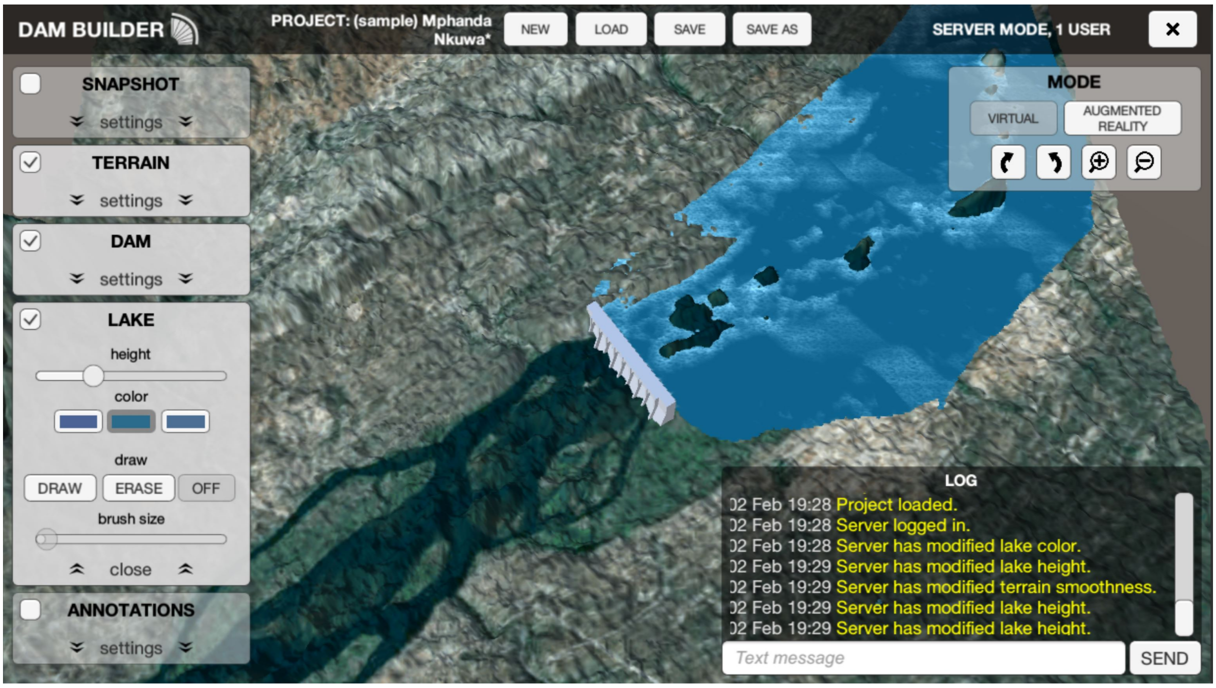


Figure 3.3: Visualization and Planning of a dam in the tool developed by Alessandro Ros [5]

This is another essential aspect of the use of AR and VR in this application, its collaborative properties in the design activity are helpful for developers, engineers, and architects to interact and create a better environment for the planning of these kinds of large infrastructures.

Adrian H. Hoppe [16] studied the current state of collaboration via the use of VR and AR tools in a situation where local workers need to collaborate with a remote expert in complex virtual data. In this solution, the worker and the expert had to collaborate to test whether VR and AR were improvements while exchanging information to locate a block that would be pointed out with VR in comparison to simply using plain images for the same effect. As expected, the end results showed that, despite still having room for improvement, collaboration using AR/VR technology made the process of locating the block a much faster experience.

3.3 Immersive Analytics

Immersive Analytics makes use of interactive technologies such as VR and AR to support the analysis and visualization of data. In this topic, Burkhard Hoppenstedt [17] researched the applicability of Immersive Reality in mixed reality and sought to discover how cluster recognition and outlier recognition were different when also trying to evaluate spatial sounds, performance, and expert status, all while comparing between an immersive analytics approach and a desktop-based approach. This work showed that not only are immersive analytics a great alternative to traditional visualizations but that spatial sounds make analysis and visualization much less time-consuming.

Santiago Bonada [18] developed a system that allows each person's view to influence their retrieval of information from a specific graph combining eye-tracking technology with large displays of data to try and see if visual analytics could become egocentric without it disrupting the collaborative experience of the activity. This solution's findings showed that with the ever-increasing affordability and fidelity of eye-tracking technology, this method will need to start being considered by designers because it contributes to better visualization of data due to its many possibilities like dynamic charts that may change when you look at it with a different focus or different angle, or even the possibility to overlay data when the user is focusing on something that may require another graph for a better understanding.

To allow users to visualize map data in different ways, Yalong Yang [6] used virtual reality to create a tool called Tilt Map (Fig 3.4) that allows users to interact with the angle at which the prism map is displayed, in other words, the user can tilt the map into a vertical position creating something that's similar to a choropleth map or they can tilt in the opposite direction, allowing them to visualize the data as if it was a bar chart.

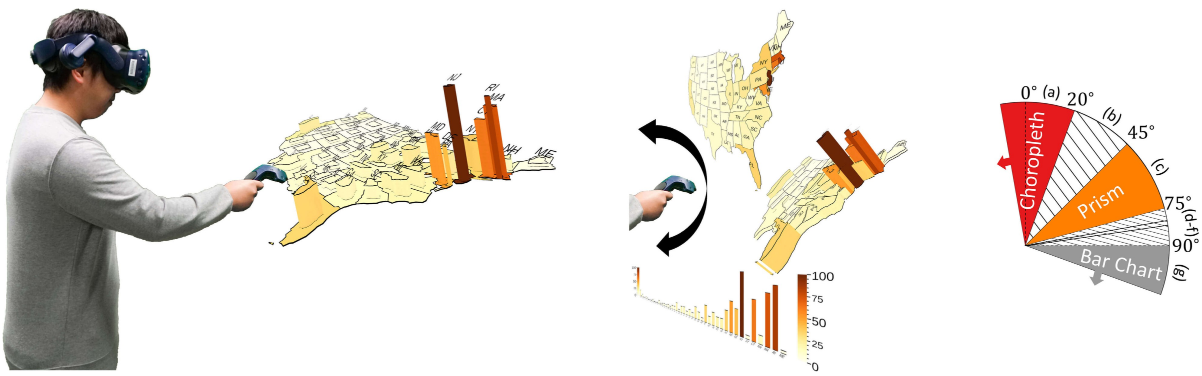


Figure 3.4: User tilting a choropleth map in Tilt Map [6]

The possibility of changing the prism map viewpoint and direction in the immersive environment was a factor that decreased the difficulty in finding an occlusion-free viewpoint from which users could spend less time analyzing the prism map data. Not only that but the studies also showed that there was an improvement of accuracy, time, and user preference when using the Tilt map in comparison to the three different visualizations that are possible in the tool displayed side-by-side.

Alexander Achberger [7] proposes a tool that he called Propeller Hand (Fig 3.5) that aims to explore other areas that current VR systems do not explore in much detail, such as force feedback and haptic feedback, even though the latter is starting to be supported in most VR/AR systems but typically, they only focus on visual and auditory output from the user. The Propeller Hand is mounted on the back of the user's hand and allows users to receive kinesthetic feedback through forces and torques but still allows them to interact or hold objects at the same time.

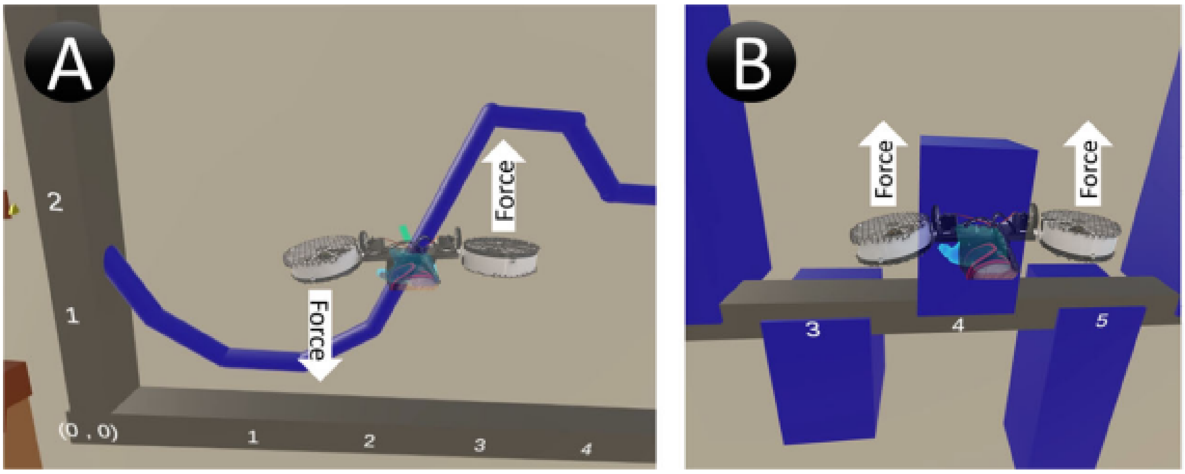


Figure 3.5: Illustration of how the Propeller Hand works on various charts [7]

The studies showed that the solution enabled a greater level of immersion in VR with participants reporting that could properly feel the different weights and directions of objects, the torque when grabbing daggers and a difference in the torque when grabbing different objects, the strength of impact when items fall to the ground and that all of this permits better visualization of the data itself.

To assist clinicians to interrogate the information surrounding their patients, Chng Wei Lau [19] created a solution that intends on analysing data regarding the gene expression and clinical data of a cohort of cancer patients. This solution is intended to use immersive technologies in order to give domain experts an easier way to navigate and make discoveries based on genomic similarities that could be important in the treatment of cancer patients or to develop a personalized treatment. This approach includes traditional 2D visualizations such as box plots, scatter plots, heat maps, and histograms but with the possibility of isolating and highlighting data through the use of its immersive capabilities. All in all, domain users reported overall satisfaction using this solution, highlighting the possibility of engaging with data and seeing its relationships in the immersive space.

Wolfgang Büschel [8] developed MIRIA, a mixed reality toolkit that allows a form of in-situ data exploration by embedding AR visualizations with spatial interactions of where the physical locations were initially recorded (Fig 3.6). This solution supports the visual analysis of not only 3D tracked trajectories based on the movement of people in the environment, mobile devices paths, and virtual camera paths but also 2D views so that one is able to visualize steps on the floor, touches on the display screen and other events that a user may perform during his utilization time which means that these 2D views are essentially projections of the spatial data.

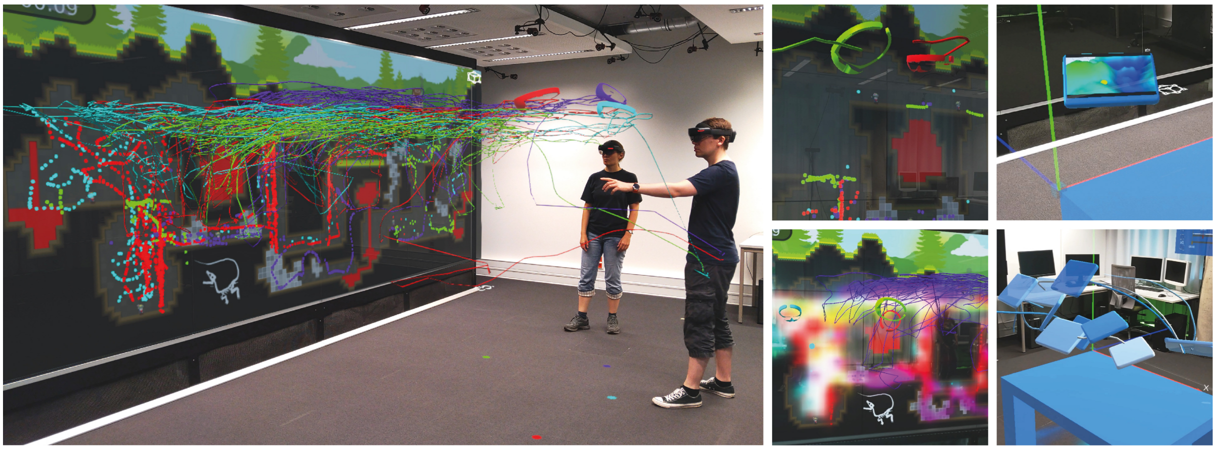


Figure 3.6: Visualization of previous meetings information using the MIRIA system [8]

MIRIA was reported to give analysts a better sense of the scale of the movement paths and their interactions with objects that happen during collaborative activities which would have been harder if done with traditional tools since MIRIA's in-door environment deployment is easy and flexible enough to be used often.

Again using a tabletop, Simon Butscher [20] developed ART, a system that aims to leverage the strengths of AR environments, combining them with a touch-sensitive tabletop, the AR is responsible for the 3D visualizations above it. This combination enhances the interaction of the system since it's easier than interacting using mid-air gestures as already described above. ART displays multiple scatter plots with linked data points, creating something similar to a multiple coordinates plot but in 3D, and the fact that it's interconnected with the touch-sensitive tabletop makes the operation much more fluid.

For this solution, users were successful in performing a combination of tests that included the identification of high-dimensional clusters and their respective outcomes, the investigation of high-dimensional data on multiple aggregation levels, the analysis of chronological trends, and the identification of outliers within the data.

3.4 Immersive Analytics in Architecture, Engineering, and Construction

Barrett Ens [9] created Uplift, a solution that seeks to combine the tabletop's interactive surface with the potential of AR, this way, users are not only limited to AR's mid-air gesture input but can also use the multi-touch surface of the tabletop to select 3D models and manipulate them and create 3D visualizations around them (Fig 3.7). For this work, a 3D campus model was developed using the tabletop as the geographical model, where users can toggle between different visualization methods, tangible widgets such as buildings that provide a physical reference for the embedded data visualization, and AR to visualize the data over the physical model, with the possibility of choosing between 2D or 3D visualizations.

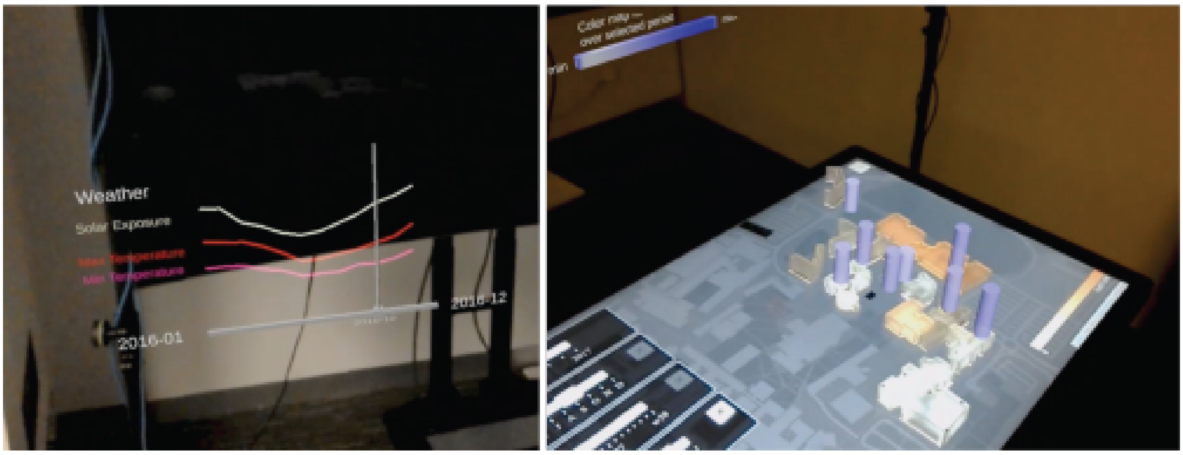


Figure 3.7: Illustration of a user using Uplift to get information about a building [9]

The participants in this study have reported that Uplift provides an intuitive overview for identifying patterns in a geographical model such as this one, which is important in collaborative activities like this one since it improves the sharing of knowledge among the users and creates a higher feeling of data storytelling that facilitates the decision making and problem-solving.

To support informed discussions among stakeholders, Chi Zhang [21] proposed UrbanVR, a tool that is intended to help in all the stages of urban design (Fig 3.8), in the first phase it helps understand the implications of said model in a location through the visualization of that model in the environment and then, advanced analytics and visualization techniques to support the decision-making of designers because often, they need to compare several design options against key performance indicators such as visibility or shadowing.

The results from this solution show that users appreciate the spatial presence that an immersive environment such as this one brings, not only that it also improves the gesture interactions which are

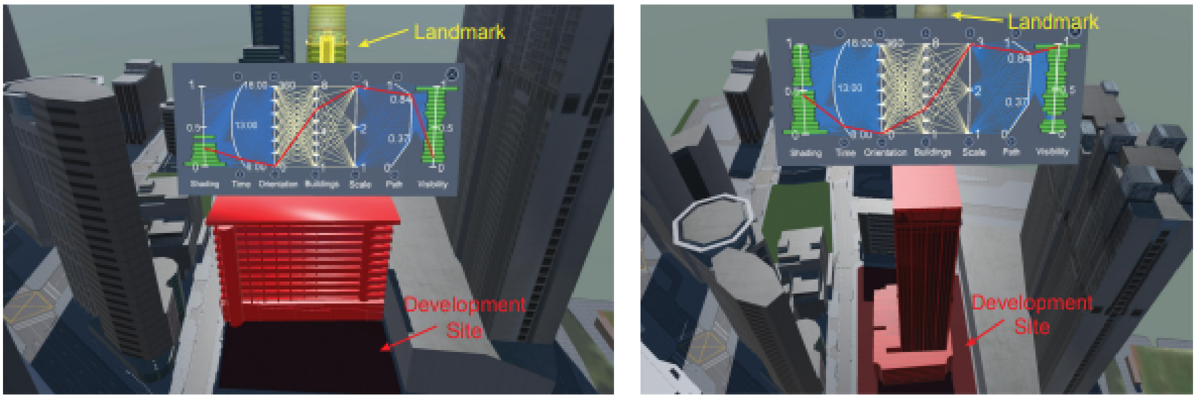


Figure 3.8: Building candidates evaluated against shadowing and visibility using UrbanVR

vital in an activity such as urban design to facilitate the visualization of complex urban scenes.

Trindade et al. [22] created DamAr, a tool that's intended to be used by dam technicians and help them in the structural inspection of those infrastructures. By superimposing the user's view of the real world with a 3D display of information derived from the process of structural monitoring, the author wants to improve the productivity and accuracy of said technicians, using data visualization interfaces that allow for interaction which will create a sense of immersion not possible using traditional approaches. With this solution, and after carrying out tests, it was clear that the use of AR tools, despite using a low-end tablet, allows for better structural health monitoring and safety control of dam infrastructures.

3.5 Discussion

In this section, we will be comparing the different solutions presented above along with all of their characteristics, advantages, and disadvantages.

Considering the traditional approaches used in the data visualization regarding dams, Peng Lin's [10] work is useful for us to assess how important it can be to have a real-time monitoring system in these kinds of large water infrastructures. We can conclude that it's helpful for both domain experts to properly monitor dam technicians and avoid fatalities/dangerous situations but it's also helpful to warn dam technicians in the event of an emergency. Just like the case of GestBarragens [11] which improved accessibility to dam's data which was something that was lacking severely in the early 00s.

The same can be said for Zhang's [3] tool which not only monitors unexpected situations but it allows for remote conferences which are useful since a dam may be located in a distant place that may not be easily accessible and therefore, communication between domain experts and technicians at the place is key, that along with visual information of the dam may prove of great value.

Regarding the use of VR/AR in AEC, Hafsia [12] presents an interesting approach on how to train construction workers for better safety practices and can be useful for situations where it's too risky to have you training in a real location of construction, however, it misses out on force feedback which is a big factor in these kinds of situations.

It was to prevent this kind of situation and to make sure that students have some collaborative experience that Tzong-Hann Wu [4] created a solution that aims to develop better safety measures for the users along with increasing their sense of teamwork which may be a good indication for our own work and how we intend to make the collaboration with professionals from other areas.

Unlike the solutions above, Oluseyi Julius Adebowale [13] aim was to use AR in order to improve productivity in a construction environment, and his work shows exactly that, domain experts can gather knowledge about the project more efficiently which is the objective of our work, we just have to keep in mind that the costs associated with these technologies may be a problem.

Xiang Li [14] demonstrated through his work regarding urban landscape design that the possibility of interaction and immersion within the data is of big help, which means that VR/AR will allow for faster reading of the situation and easier problem-solving. Despite that, there's the continuous problem of equipment cost and the difficulty of developing real-world models with large coverage.

Alessandro Ros' [5] tool proved to be valuable in the planning of large water infrastructures such as dams, not only does it allow collaboration between domain experts located in different areas of the world, its possibility of changing between AR and VR modes is something that really benefits the testing of different solutions of dam placing in a landscape. On that topic, Adrian H. Hoppe [16] studied if Virtual/Augmented Reality could be useful to improve collaboration and came to the conclusion that we can't overstate the benefits of using these technologies in a collaborative activity despite its limitations already mentioned above, it still has room for improvement.

To test whether the use of VR/AR contributes to a better detection/recognition of outliers and clusters, Burkhard Hoppenstedt [17] compared a more traditional approach using a desktop-based application against an immersive solution with the use of mixed reality. The results were clear that immersive analytics provides a deeper and easier analysis of the data and therefore, easier recognition which is also amplified by the use of spatial sounds, something that may be more explored in the future. Still, on this test, the ART system developed by Simon Butscher [20] which consisted of a plot similar to multiple coordinates on 3D projections showed the exact same results which are really promising for our own solution.

The Tilt Map [6] showed us just how powerful the ability to interact with a chart can be. In this case, the possibility of changing the prism map viewpoint and direction enabled users to extrapolate different information just by flicking their controller with the only limitation being that some charts do not have great scalability when, for example, a bar chart does have lots of bars. Similarly to this, the Propeller

Hand [7] demonstrated that the force feedback that is received by users can be advantageous to better visualize data and for users to properly measure the data itself.

On a different note, Wolfgang Büschel [8] created MIRIA, a system that was designed to track the movements and paths of users during collaborative activities and afterward, allow them to visualize in the immersive space. Also due to this system's easy deployment, we can see that this can be a powerful tool to better get a grasp of what happened in an activity that required collaboration.

With the improvements being noted after using Immersive Analytics, areas such as the AEC tried to apply it to their own domain. A model of a campus that integrated Immersive Analytics was successfully implemented by Barret Ens [9] using a tabletop and Augmented Reality. Uplift highlighted how a tabletop's multi-touch surface can improve the immersive experience for users over the traditional mid-air gesture used in AR. This same advantage was also perceived in UrbanVR [21], a tool to help in the activity of urban design, it also was implemented with a tabletop which, just like the Uplift tool, was reported to improve the interaction between the user and the environment.

4 Requirements

It was imperative for the success of our project to first understand LNEC's expectations (Fig 4.1) regarding this application. Our ability to meet these expectations would significantly influence our success rate, as the goal was to develop a tool assisting LNEC dam engineers and technicians in security and dam inspection activities.

To ensure alignment with these expectations, we conducted several key meetings with the LNEC staff. These discussions were instrumental in:

- Setting project parameters, exemplified by a case study mirroring tasks routinely undertaken by dam engineers.
- Determining which data from the Cabril dam should be focused.
- Brainstorming and discussing potential visualization methods.

Furthermore, feedback from the LNEC team was invaluable in refining the application's design. They provided insights on design discrepancies and suggested enhancements for improved user experience. This iterative feedback loop was pivotal, given our commitment to user-centered design in the development of this application.

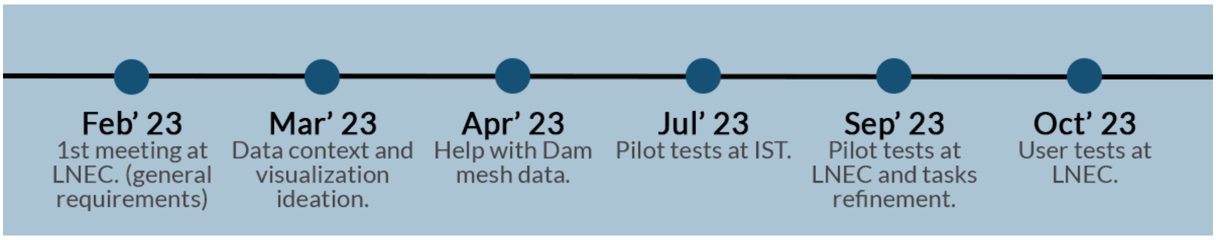


Figure 4.1: Meetings and User Tests at LNEC and IST.

4.1 General Requirements

We propose the development of a prototype that would enhance the visualization of different metrics and statistics used for the safety control of dams, with metrics such as water level, horizontal and vertical displacements, air and concrete temperature along with others that are important for dam technicians to evaluate the current state of the dam. Along with that, we will also be aiming to facilitate the visualization of the sensors that are present at the dam in order for the prototype's users to gain better insights into the environment that they are currently analyzing.

This prototype should also allow LNEC technical staff and dam technicians to visualize relevant insights in a way that permits them to accompany the evolution of these metrics for different water levels, and therefore, see the changes reflected by increasing or decreasing the water levels.

Therefore, the main requirements for our prototype are as follows:

- Allow users to visualize the placement of these sensors that are responsible for the retrieval of information vital to the safety control of the Cabril dam.
- Allow users to visualize *in-situ*, super-imposed over the dam, a dam similar to the structure of the dam, where users can manipulate the water level and see the corresponding dam displacements, along with color information for a better understanding.
- Allow users to observe and compare the observed displacements, tracked by the sensors at the dam, and the computed displacements predicted by the mathematical model ran at LNEC.
- Allow users to visualize three different modes of oscillation of the dam, each mode corresponds to a different frequency that changes depending on the water level.

This prototype is primarily designed for use by dam technicians and the LNEC technical staff who possess expertise in and are engaged in the monitoring of the Cabril dam. Users should be able to swiftly identify sensor locations and, through a user-friendly interface, toggle between different visualizations. Additionally, the interface should allow easy manipulation of data, particularly the water level and the scale of the visualization. Options to modify the dam mesh should also be accessible, enabling dam technicians to visualize the displacement and mesh oscillation in various ways.

4.2 Data

The Cabril Dam is equipped with sensors and tools that generate substantial volumes of data. This data is archived and utilized by the LNEC staff. It encompasses a range of measurements, from horizontal and vertical displacements—indicating the dam's relative movement at various water levels—to temperature readings at multiple dam locations, and even water levels in both the reservoir and downstream.

During our meetings at LNEC, it was identified that the most relevant data for our use cases was the evolution of both the horizontal and vertical displacement with the variation of the water level. This applies both to readings taken directly from the dam's sensors and those projected through finite element numerical models. Other than that, the data detailing the dam's oscillation, for three vibration different modes is also vital for our application.

Lastly, LNEC provided us with positional data. This facilitated the programmatic generation of a dam mesh, which is integral to our visualization efforts.

Therefore, the main requirements datasets provided by LNEC were:

- Computed Displacements: Contains positional data, x, y, z coordinates of the position of the dam for different water levels ranging from 180m to 297m.

- Observed Displacement collected by geodesic marks: Contains the displacement value at that sensor to be represented for different water levels ranging from 180m to 297m.

- Oscillation Positional Data: Contains positional data, x, y, z coordinates of the position of the dam for three different modes of vibration. Each mode has its own frequency that varies with the water level.

- Dam Mesh Positional Data: Contains x, y, z coordinates of the position of points that can be used to create a 3D mesh of the dam.

Even future work aims for seamless integration with LNEC's databases to visualize real-time data, for this prototype, we utilized data provided in XLS (Excel Spreadsheet) files. This data was subsequently analyzed and cleaned using Python, then converted to Comma-separated Values (CSV) files. Upon launching the prototype, these files are loaded and employed by the application.

The Dam Mesh Positional Data (Fig 4.2) provided by LNEC allowed us to create a 3D mesh of the dam, this is especially important in order to have a super-imposed model of the dam over the original model. This mesh will be used to observe the effects of the displacements applied on the mesh, and to compare it with the original model, to better see the differences along with other various views.

During one of the meetings at LNEC, it was discussed how these 3D models could be incorporated into our work, which proved to be vital and an integral function of our application. These models were

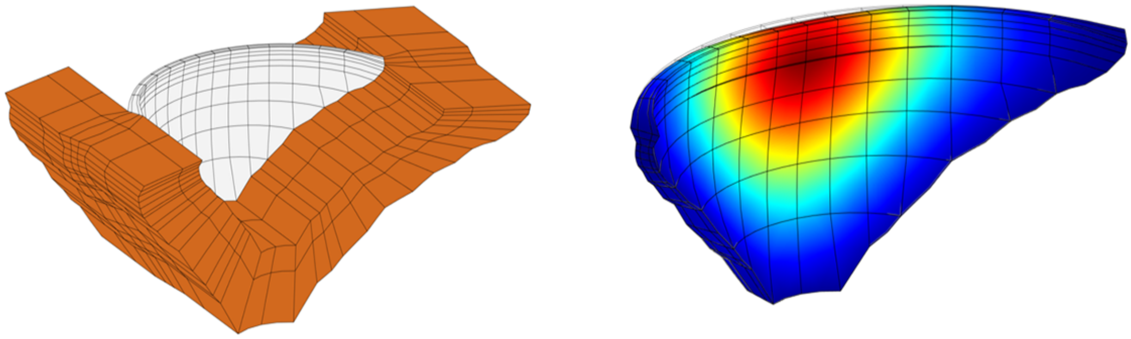


Figure 4.2: 3D Model of the Cabril Dam, in Matlab.

generated in Matlab and later exported to datasets of nodes and elements, which were then provided to us.

4.3 Equipment

For our work, we researched and analyzed a set of different virtual reality systems. Some of the functionalities that factored into our analysis were:

- Wired or Wireless - Whether it's possible to use the system without a cable, which is obviously an advantage over a system that requires a cable since it limits our movement depending on the size of the cable.
- Refresh Rate - Indicates how often a system updates or renews its data, typically measured in times per second.
- XR - Whether the system allows for VR or AR or both options.
- Price and Disponibility.

In the end, we opted for the Meta Quest Pro. This device is not only renowned for its exceptional visual fidelity and user-friendly interface but also for its advanced tracking features, expansive content ecosystem, and wireless freedom. Its robust processing capabilities and ergonomic design further position it as a leading choice in the world of virtual reality, ensuring that our research and application requirements were met with precision and efficiency.

4.4 Use Case

The Unified Modeling Language (UML) Use Case Diagram in Fig. 4.3, exemplifies the use cases for our VR prototype, for the inspection and control of dams. The actors would be the dam engineers and technicians who work on the structural control and inspection of dams, and it is intended to be a visualization application where the actors are capable of seeing the position of sensors in the dam and viewing observed and computed displacement along with an animation that resembles the dam oscillation for three different vibration modes. The technicians and engineers can interact with a UI which will allow them to select a specific water level, regulate the scale of visualization, and many other options that seek to enhance their day-to-day work. The development of this project aims to implement all the mentioned features in the virtual reality space.

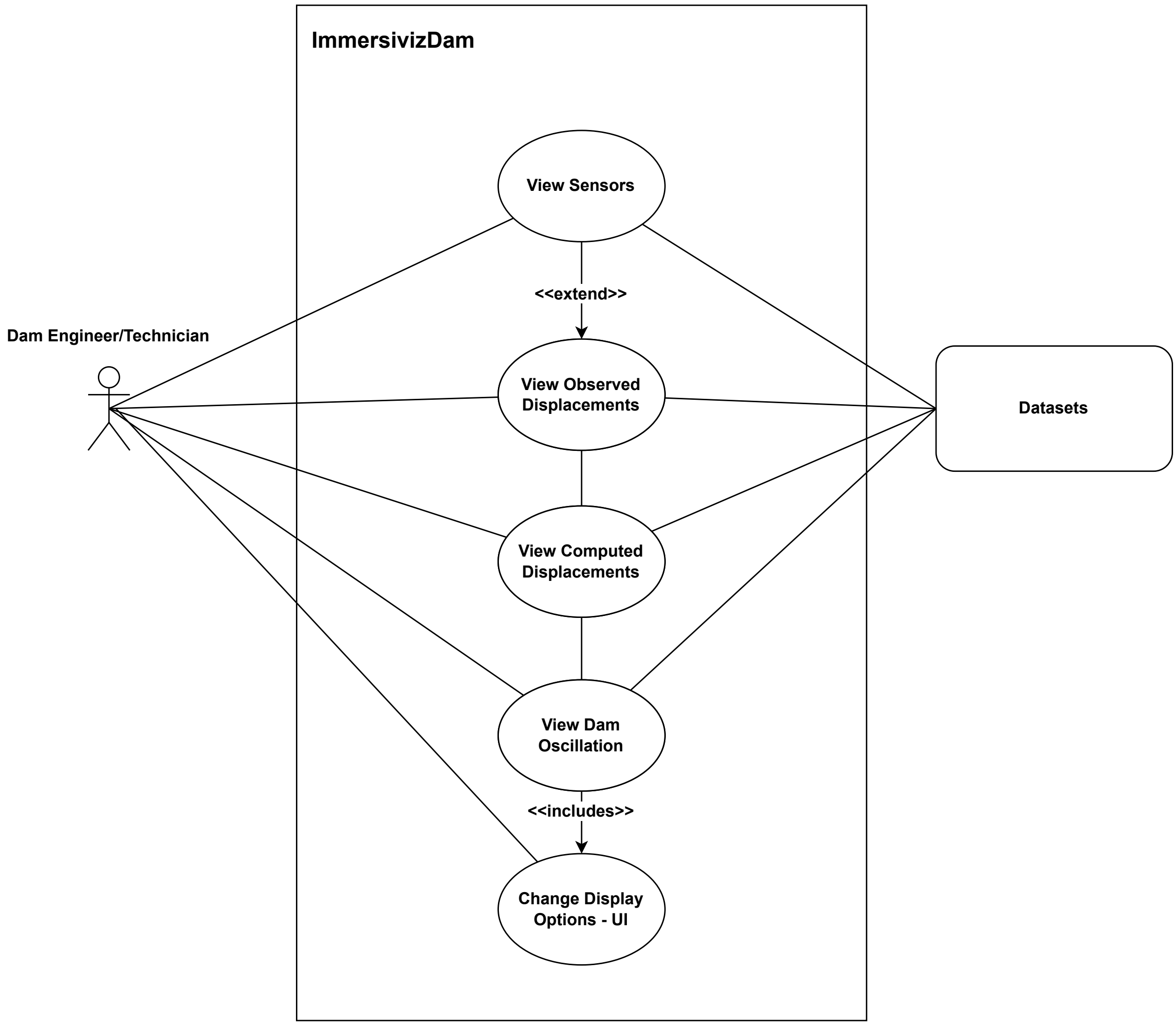


Figure 4.3: Use Case Diagram of ImmersivizDam

5

Prototype

Based on the requirements gathered after several meetings with the LNEC staff, we built a prototype named ”ImmersivizDam” following the principles of user-centered design development. This prototype aims to use new technologies such as virtual reality to enhance and facilitate the work of dam engineers and technicians, by providing users with a sense of immersion and presence within the data.

5.1 Architecture

Our prototype was developed to demonstrate how employing virtual reality and 3D visualization in an immersive environment can enhance the structural control and inspection of significant Civil Engineering infrastructures, like dams, compared to desktop-based visualizations. In this sense, this work aligns with the larger XR4Dams project by LNEC, which investigates the practical applications of these tools in its routine activities.

This prototype serves as an initial step towards developing a functional extended reality tool for dam technicians and engineers. While we've chosen a simpler approach in certain areas, we've ensured the design preserves the possibility for future enhancements and subsequent improvements. In the future, the goal would be to integrate this tool with LNEC's data on the Cabril Dam and by superimposing a mesh similar to the dam, allow users to visualize and interact with real-time various statistics regarding the functioning and operation of the Cabril Dam, allowing them smooth and continuous monitoring and inspection, without needing to be physically present due to its immersive capabilities, to further improve its safety and control.

Our VR application is comprised of three primary modules (Fig 5.1). These modules collaborate to present cohesive and insightful data visualizations, drawing from the structural monitoring data collected by sensors within the Cabril Dam.

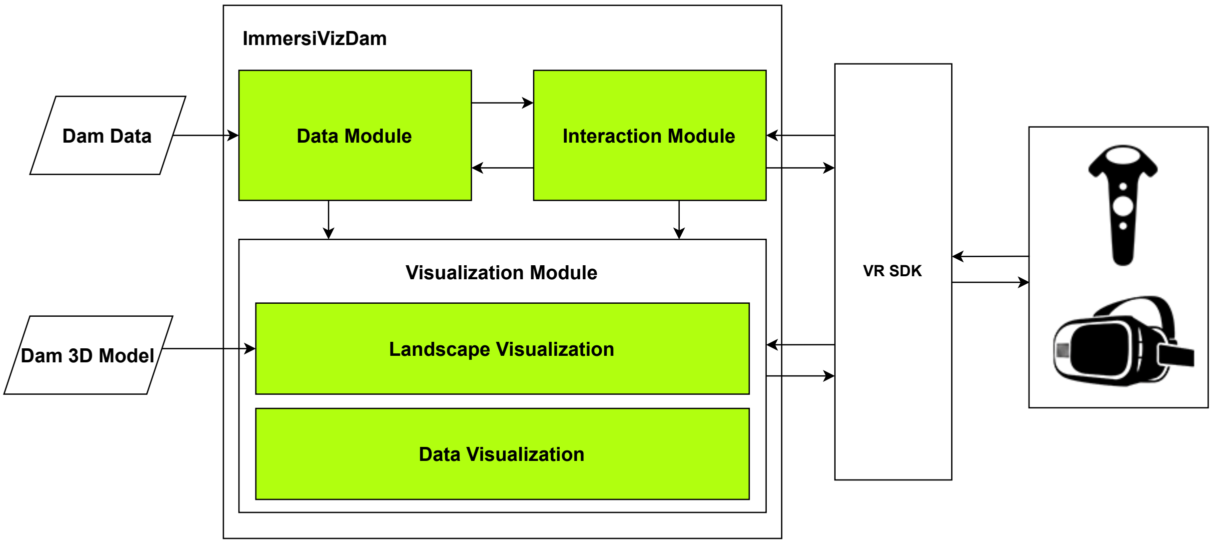


Figure 5.1: System Architecture

The Data Module is the component of our app that is responsible for receiving data. This data is generated by the sensors within the Cabril Dam and from LNEC's expected finite element numerical models. It will be received in the form of CSV format files, which were cleaned from spreadsheets provided by LNEC. As mentioned above, even though we will be currently using static files in our approach, our main goal would be to have our application receive the data in real time from LNEC's databases.

After receiving the data, this module loads it and parses it into a suitable format, this data will then flow to the Interaction Module and into the Visualization Module as shown in Figure 5.1.

The Interaction Module is the component susceptive to the user's input, it receives the data from the Data Module, and depending on the user's interaction, it has the ability to change the data that is displayed in the Visualization module while also having the ability to calculate new metrics on the current data for a different kind of visualization which implies a change in the data, or to just simply save the state of the application through its connection with the Data Module. Therefore, the interaction module can be considered our most important module, since its objective is to connect the user, with the data and what's to be visualized.

The main objective of our work is to demonstrate that we can develop a tool that takes advantage of VR to create an immersive experience that can improve the structural monitoring and inspection of dams. As a result, user interaction has been one of our main focuses and the reason we are using a VR SDK to make the connection between our VR system, more specifically, the controllers and the Oculus. This module is what allows us to track the movement and interactions of the user with the VR equipment and transmit it to our Interaction module, from there, the Visualization and Data module will be manipulated to create the immersive experience wanted by our users.

Finally, the Visualization module is responsible for rendering both the landscape, created by my fellow colleague Raquel Chin's work in developing an Immersive Tour of the Cabril Dam, and the data that is displayed to the user. This information is transmitted through the VR SDK to the Oculus which can also alter the current visualization. This will allow us to create the Cabril Dam environment, which corresponds to the landscape visualization, and then superimpose over the 3D model of the dam, a mesh similar to the dam's structure where users will be able to observe both displacements and different modes of vibration. All of this, and the sensors represented in the wall of the dam correspond to the data visualization.

Our solution will follow the "Model-view-controller" (Fig 5.2) software architectural model (MVC), represented in Fig. 5.2 meaning that each one of our components will be responsible for one of these functions. Namely, the "Model" is represented by the Data Module, the "Controller" corresponds to the Interaction Module, and the "View" consists of the Visualization module. In our system, the user is able to interact with the "Controller" in order to manipulate the data and is able to see the result of that interaction in the "View".

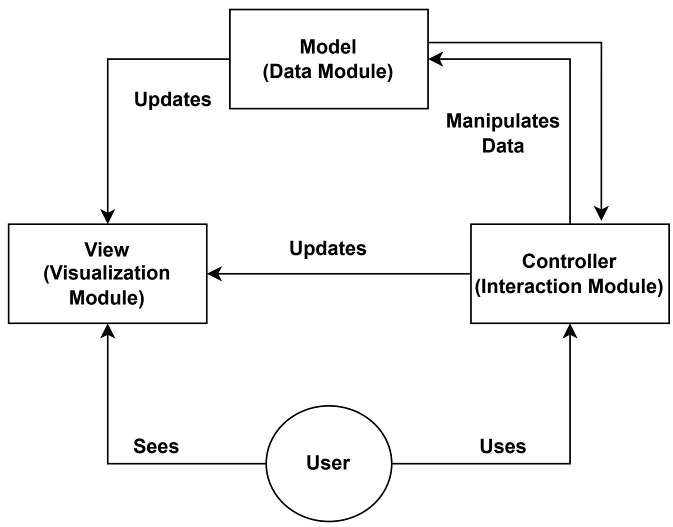


Figure 5.2: Model-view-controller architecture of the system

This application was developed to be displayed in VR systems such as the Meta Quest. These systems, despite being very expensive and not affordable for most users, are one of the best options for VR development. Nonetheless, some problems like the headset refresh rate and the fact that is not suited for long-term use are still present, even though many improvements have been made in that sense in the last years.

5.2 Implementation

Our prototype was built through multiple phases of development. An experimental version was first created using a 3D model of the Cabril Dam provided to us by LNEC, and its intention was to set and investigate the feasibility of some of the applications intended for the prototype along with its UI. In the second phase, closer to the first pilot tests, our prototype was integrated with the landscape created by my colleague and was finally integrated with the actual VR system.

5.2.1 Technologies

For this work, we had to ascertain which technologies would be the best fit for our prototype before the implementation even began. We also had to make sure that our choices would be compatible and simple to implement on the VR system of our choosing.

After reducing the choice of graphical engine to two options, Unity and Unreal Engine, after evaluating both advantages and disadvantages, we decided to move along with Unity, with its user-friendly interface, which boasts a shorter learning curve which is particularly advantageous for those new to game design or those working in academic settings. Furthermore, Unity's extensive asset store and the ease of multi-platform development make it a versatile choice for diverse projects. While Unreal Engine is undeniably powerful and offers high-fidelity graphics, Unity provides a balance of functionality, accessibility, and flexibility, making it the preferred choice for this thesis.

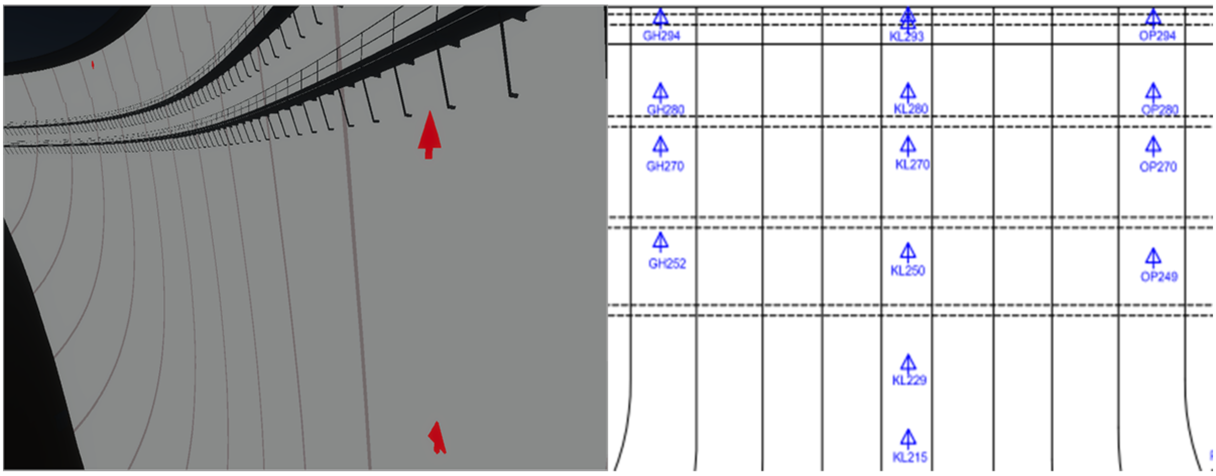
The programming language of our choosing was C# (C Sharp) due to its compatibility with Unity and the vast documentation available which would prove to be key in our development.

Given our choice of the Meta Quest Pro as our primary development device, it was logical to select the Oculus Integration as our VR SDK. This choice was influenced by its seamless integration with Unity and compatibility with our VR device. The SDK offers a plethora of valuable assets for our application. However, it's worth noting that some of the SDK's documentation is outdated.

5.2.2 3D Models and Sensor Representation

In our prototype, the first thing worked on, involved setting up the scene with the 3D model of the Cabril Dam provided by LNEC and representing sensors on its wall, these sensors would be geodetic marks that track the displacements of the dam.

After carefully assessing how to represent them, we had to explore and research what would be a good representation in 3D of these sensors. The initial idea was to represent them close to their real-life design, but after trying it, we decided against it because of its poor representation at a distance. After that, we decided to use a symbology that dam technicians and engineers would be familiar with, and eventually chose to use a similar representation to the one used by LNEC staff on the blueprints of the Cabril Dam provided to us on a Technical Note [1] (Fig 5.3).



(a) Geodetic marks represented on our prototype.

(a) Geodetic marks represented in the Technical Note.

Figure 5.3: Geodetic Marks Design

In this first phase of development, we had to come up with a mesh representation to be superimposed over the actual 3D model of the Cabril Dam. Luckily, LNEC provided us with positional data of over seven thousand nodes that would allow us to be able to represent a mesh that resembles the structure of the dam and could be used to visualize information superimposed over the 3D model.

This information was given to us in the form of two separate spreadsheets, the first one contained the positional data for all the nodes, their x, y, and z coordinates, and the second one contained all the elements, and their respective nodes, used to be able to build the dam mesh. This mesh (Fig 5.4) was entirely built programmatically, which proved to be increasingly important whenever we needed to implement other features on the mesh due to its accessibility in being modified since it's not a static object and instead, built in a coded manner. This meant that the dam mesh was a collection of multiple triangles built from each set of three nodes.

After successfully rendering the dam mesh for visualization, we observed certain visual irregularities that were initially unexpected. These glitches, while minor, could impact the overall comprehension of the visualization. Fortunately, our decision to construct the mesh programmatically via scripting proved

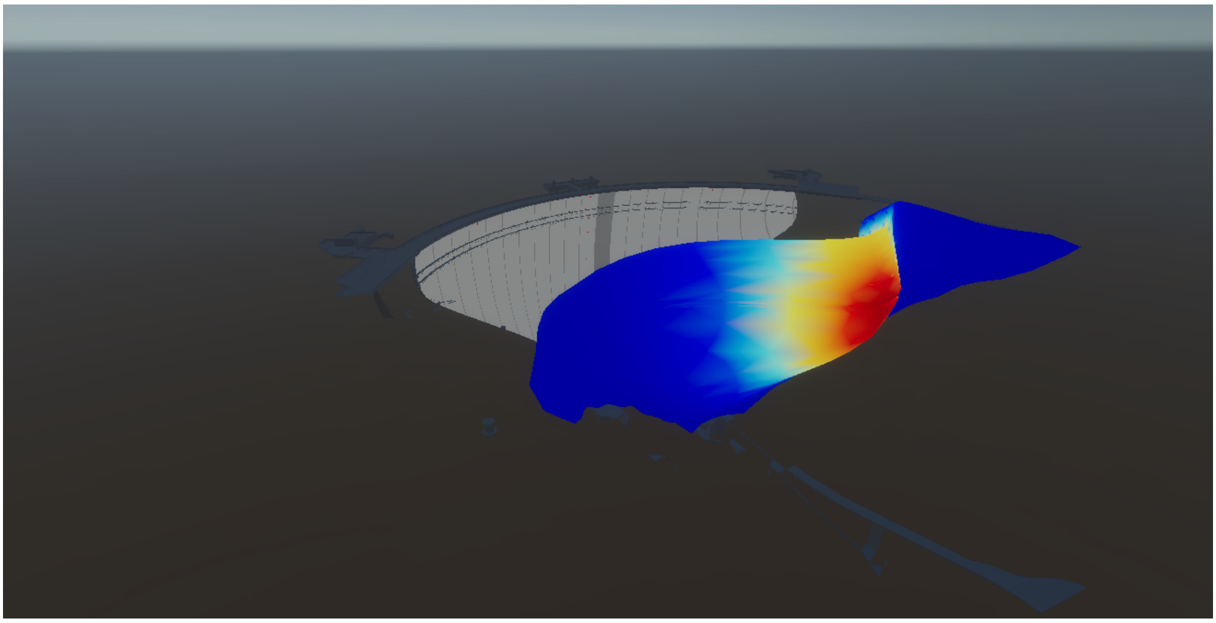


Figure 5.4: Initial Dam Mesh superimposed on the 3D Model of the Dam

advantageous, enabling us to swiftly and precisely address these inconsistencies. This approach not only expedited the debugging process but also ensured a more refined control over the mesh details. To enhance clarity and the overall user experience, we strategically emphasized the edges between each mesh element. Additionally, we opted to remove the internal triangles (Fig 5.5). While these triangles added depth, they detracted from the core visualization objectives, and their elimination led to a clearer and more focused representation.

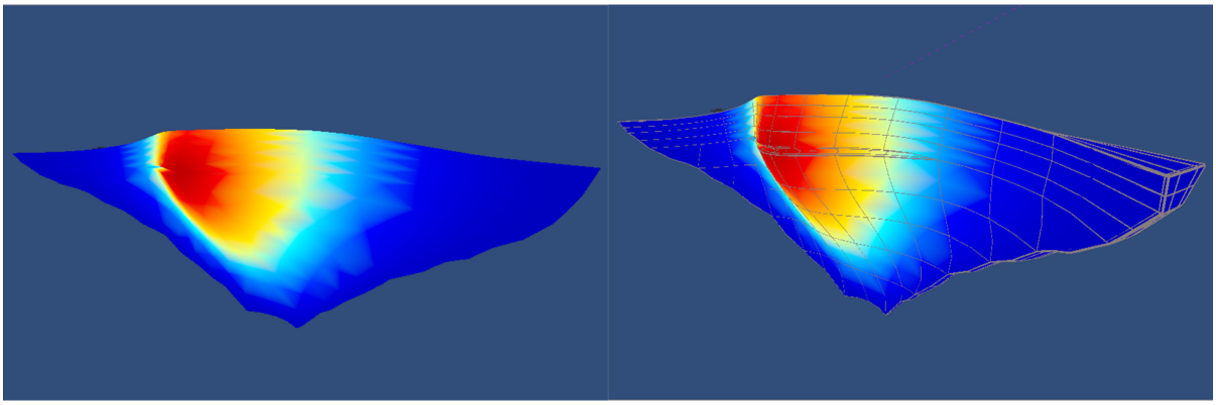


Figure 5.5: Dam Mesh design evolution

It's also worth noting that during the development of this prototype, my colleague Raquel Chin was also working on the Immersive Tour of the Cabril Dam, this meant that the final version of this prototype would be able to have the dam mesh superimposed over the actual landscape, with a different 3D model for the dam, along with models for the terrain and the water in the reservatory and downstream (Fig 5.6).

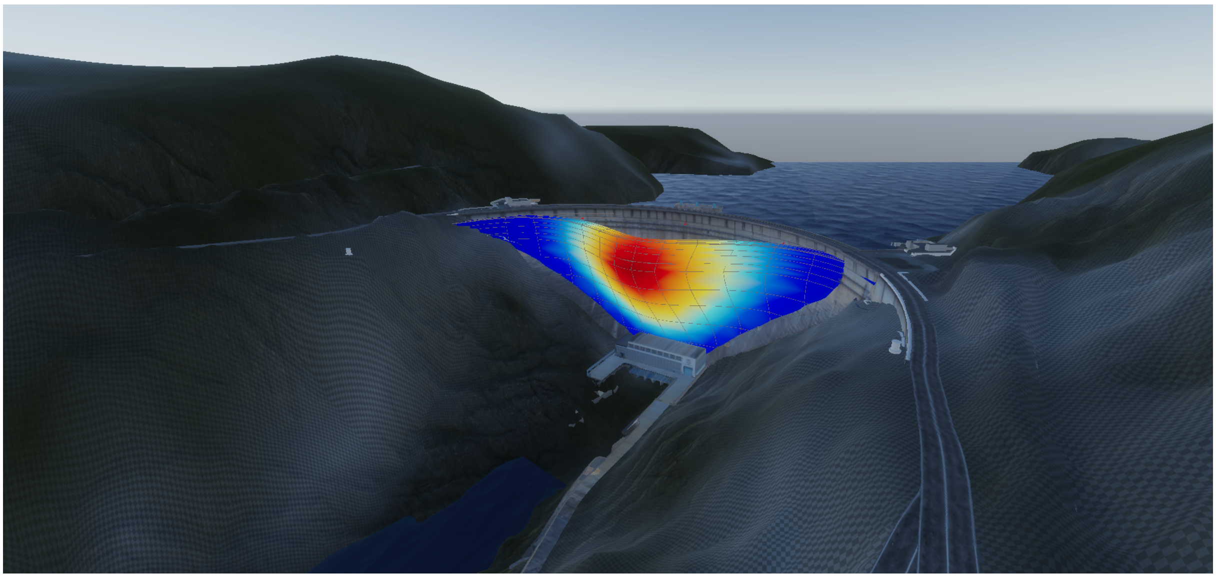


Figure 5.6: Overview of the dam mesh superimposed the final dam model

5.2.3 User Interface

We developed a UI that would allow dam engineers and technicians to interact and manipulate the data that is displayed and superimpose the real structure. We took into consideration that the UI shouldn't be overcomplicated since our users may not be familiar with the use of VR devices and could not be tech-savvy. So, using a user-centered design development, we designed something that was easy to use and learn.

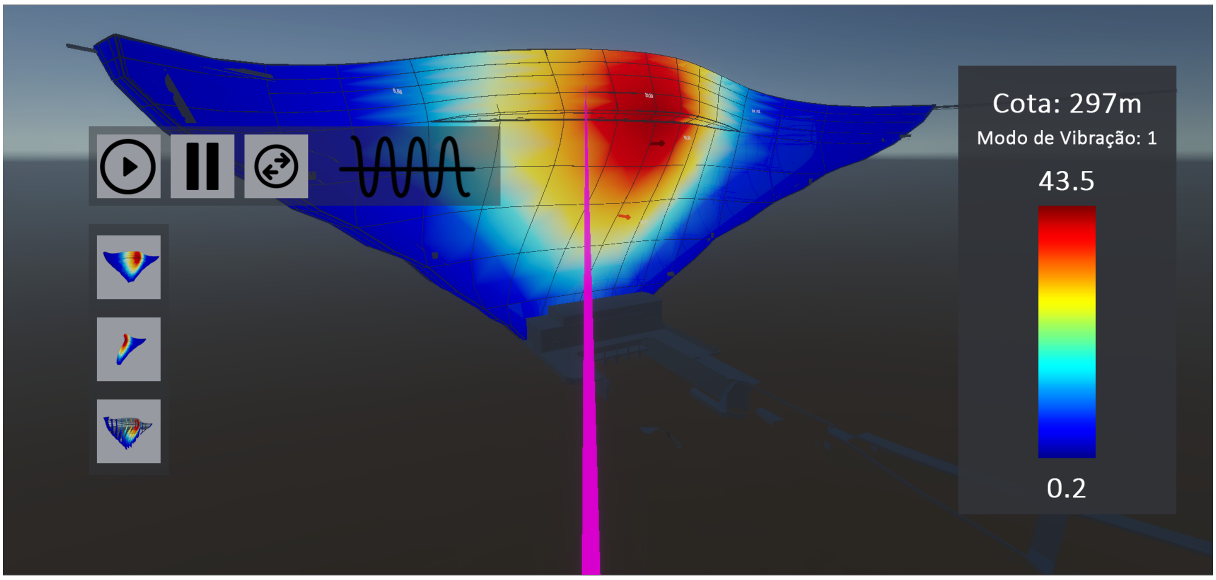


Figure 5.7: First Sketch of the UI

The initial sketch of the UI (Fig 5.7) was intended to be as simple as possible, it included a set of buttons that would allow the users to change the shape of the dam mesh, allowing for more than one mesh visualization, along with buttons that would serve the purpose of playing and stopping the oscillation animation of the mesh. On top of that, users were presented with information that would explain the values that they may be visualizing.

In the start screen, represented in Fig. 5.8, the user is presented with a small menu that includes four different options that match the four different visualization options in our prototype. Initially, this menu was created without the text labels aiding the labels, but after experimenting, we concluded that we must have an auxiliary text to aid users in selecting and knowing which option has been selected. Additionally, we added a reset button that served the purpose of resetting the application entirely.

Figure 5.8: UI Start Screen

When clicking on the second button, from top to bottom, the UI (Fig 5.9) will reflect that change, adding two additional layers on top that provide the users with new options to customize their current visualization. In this mode, users may adjust the water level to their liking and see those changes mirrored in the observed displacements that are represented by arrows in front of their respective geodetic mark.

As we were developing the prototype, we figured out that changing the water level to a specific number was a hard task due to VR's intricacies when selecting a slider and adjusting its position. In order to mask that problem, we added two buttons that could level up or down the water level and therefore, add a level of certainty to the scaling. On top of the UI, we added a panel that indicates the maximum and minimum values of displacements for the selected water level.

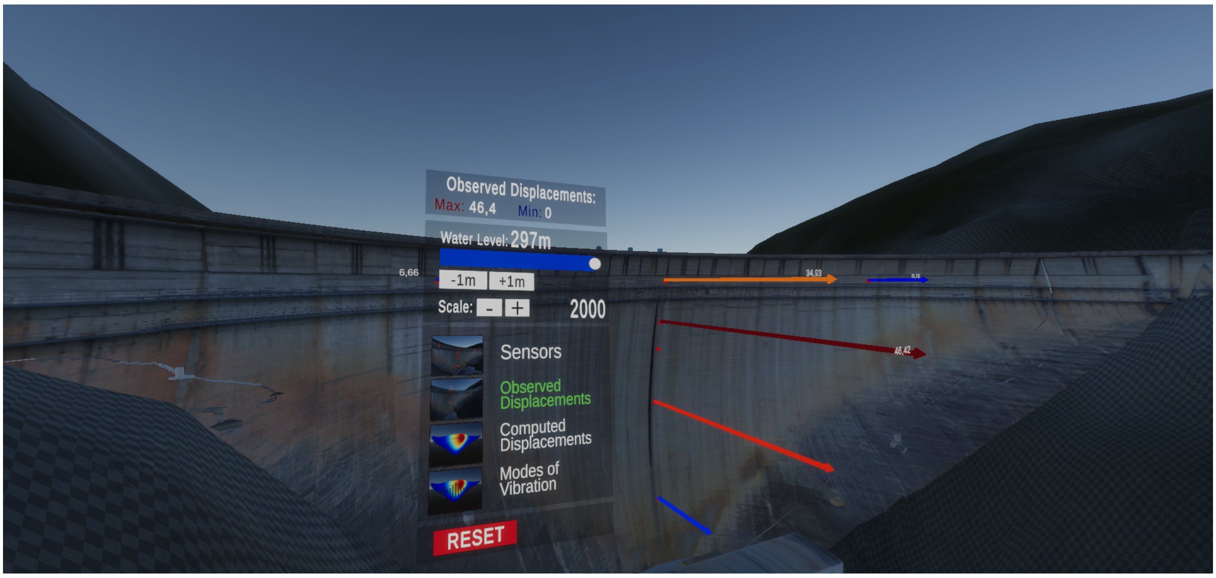


Figure 5.9: Observed Displacements User Interface

A user can also select the third button in the initial screen, from top to bottom, which would take him to the Computed Displacements mode (Fig 5.10). In this mode, two new layers get added to the UI when compared to the previous mode, with them being a layer that serves as a horizontal scale for the colors belonging to the displacements displayed in the dam mesh. On top of that, we have a layer with four buttons that help the user select a more suitable visualization and aid them in comparing the observed displacements with the displacements computed by LNEC's expected finite element numerical models.

From left to right, these four buttons offer users the following functionalities: display only half of the dam mesh, revert to a view of the entire mesh, focus solely on the dam's joints for a detailed perspective, and reset the view.

Finally, when the last option of the initial screen is selected, a user is shown the dam mesh (Fig 5.11), in this mode, the 3D model of the Cabril Dam is not in view so that the oscillation of the dam is better displayed. When this is clicked, a new layer appears on top of the water level selection layer. This layer is capable of playing and stopping the animation, when clicking on the first button, from left to right. The missing button is responsible for changing the current mode of oscillation, cycling between the three different modes. When changing the mode of vibration, the frequency is also updated on the new layer of the UI.

Following initial tests with the prototype, we trialed having the UI spread across both sides of the user's vision. However, we found this to be overly obtrusive and ultimately opted for a design focused solely on the user's left side. Additionally, while we did experiment with the UI's positioning, we eventually favored a head-tracked UI over one positioned by the user's left controller. This decision was influenced by the controller's slight pulsation, which introduced potential confusion. We also added the option of

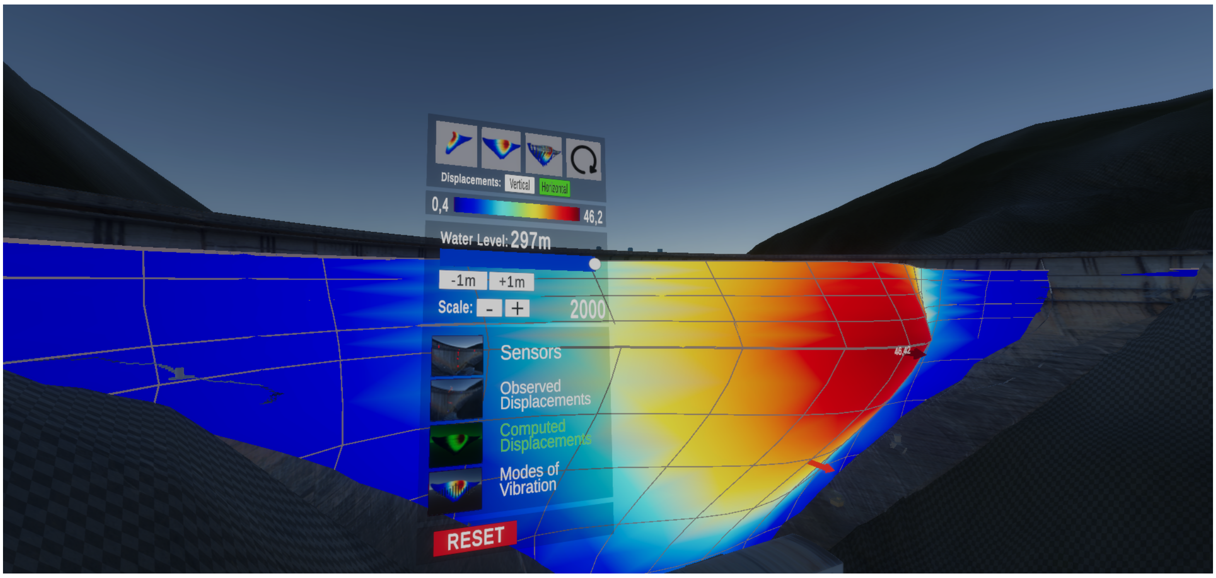


Figure 5.10: Computed Displacements User Interface with the dam joints selected

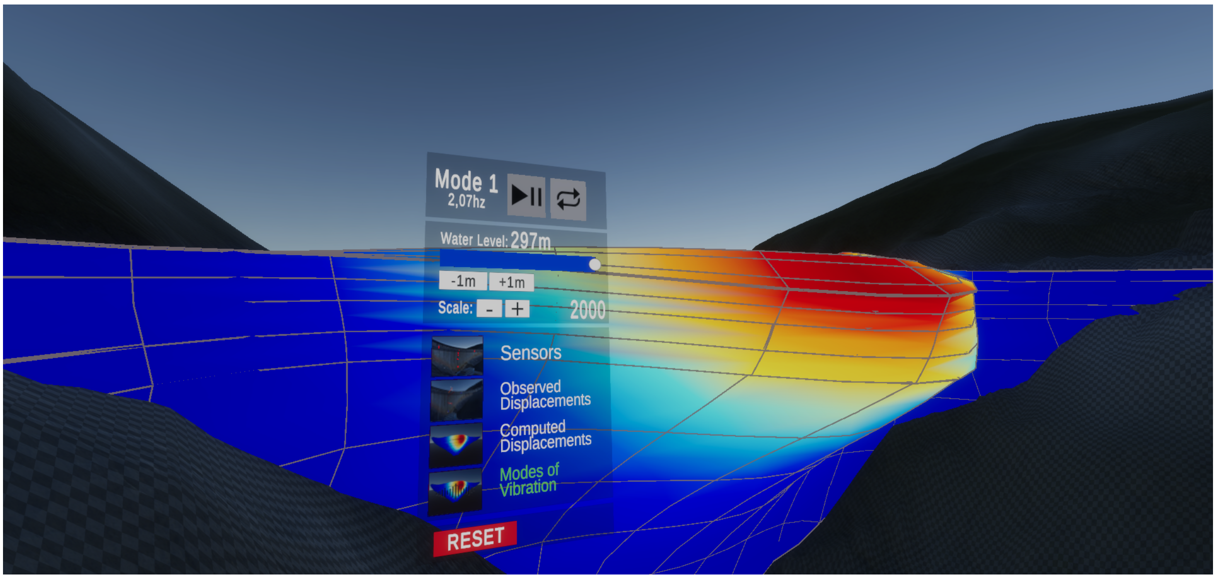


Figure 5.11: Modes of Vibration User Interface

letting the user click on a button on the controller and be able to hide the UI for an even more immersive experience.

5.2.4 Operation

Upon completing the features – the 3D models of the Cabril Dam and its mesh, along with the UI and its functionalities – we integrated them to craft a functional prototype. This prototype was developed and compiled using Unity. While exporting the application and transferring it directly to the VR device was an option, we chose to connect the Meta Quest Pro to the computer and run the prototype using the link cable. When starting the application, the user will be greeted with the Cabril landscape and 3D modal, with the respective geodetic marks represented on its wall. From here, users can start interacting with the UI and adjust their movement on the application using both controllers.

Finally, this prototype was created to be a first step toward building a functional and useful tool for dam engineers and technicians, and so we try to validate this idea in the evaluation phase, described in the next section.

5.3 Challenges

During the development of the prototype, there were several challenges that had to be addressed in order to keep the flow of development going. One of the biggest ones that we faced was inexperience with the Unity environment. Even though Unity is considered one of the most accessible interfaces for interactive content creation, starting from square one presented notable challenges. Unity's ease of use and extensive selection of learning resources make it an ideal entry point for newcomers. However, the initial phase was hard due to the need to familiarize ourselves with its comprehensive set of features and the specificities of the C# scripting language. The platform's extensive documentation and active community forums proved to be invaluable for our journey but despite that, it still necessitated careful navigation to separate outdated or irrelevant advice from the essential and up-to-date insights.

As we began the phase of integrating our prototype with VR, a new challenge emerged with the Oculus Integration package for Unity. Leveraging this package posed significant hurdles, primarily because of its poorly structured documentation. The provided documentation was often unclear, making it extremely difficult to integrate the prototype, initially developed for a desktop, with our VR system. This lack of direction hindered our efforts to maximize the potential of the package, leading to some changes of direction in our development process. Further complicating matters, we found that a majority of the available tutorials were outdated and not feasible for our prototype. Using unhelpful resources, which often didn't fit with current best practices, required us to rely heavily on trial and error. This not only extended the integration timeline but also introduced unforeseen challenges to our prototype and further work.

Another challenge faced during our development process was the intricate task of integrating my prototype with the Cabril landscape designed by my colleague, Raquel Chin. A primary struggle was the precise positioning of the dam mesh over Cabril's 3D dam model. Achieving a seamless alignment was paramount to the overall project's visual and functional consistency, yet differences in the methods used on both prototypes introduced complexities that we were not prepared for. Additionally, the fact that we employed different render pipelines further exacerbated the integration difficulties, in this case, my prototype was using the Universal Render Pipeline while Raquel's was using the High Definition Render Pipeline. These pipeline discrepancies, although making sense in our individual contexts, demanded numerous adjustments to ensure a unified and coherent visualization. In sum, the entire integration, from alignment nuances to rendering changes, was far more intricate than initially anticipated, highlighting the complexities inherent in merging distinct digital creations.

Lastly, designing a UI for virtual reality brought unexpected challenges. Unlike traditional UI development, in VR, the stakes extend beyond mere aesthetics and functionality to include spatial interaction and immersive experience. Within the 3D realm of VR, the interface must be both visually appealing and intuitively navigable. Striking a balance between ensuring that the UI is easily navigable and not losing any immersion, as well as accommodating the diverse interaction methods possible in VR, introduced layers of complexity that we were not accounting for. These considerations highlighted the nuanced intricacies involved in creating a genuinely user-centric VR UI experience.

6

Evaluation

In any technological environment, especially one that is developed with the use of extended reality, comprehensive user testing is fundamental to a good understanding of its successes and failures. This section delves into the approach used to assess the efficacy and usability of ”ImmersiVizDam.” Here, we will explain the methodologies utilized, the specific facets of the application we were aiming to test, and the rationale behind our challenges to the users. By shedding light on this evaluative phase, we are aiming to get a transparent view of our user-centric insights derived from the test, which are incredibly helpful in shaping the final iteration of this work.

6.1 User Evaluation

With the tasks given to our users, we are aiming to get insights that would provide us with information about the accessibility of our UI and the ease of performing tasks similar to the ones done by dam engineers and technicians (Fig 6.1).

Figure 6.1: Test Setup at LNEC

6.1.1 Evaluation Approach

The central objectives of our tests for this work were to ascertain the effectiveness and practicality of our UI. Given the immersive nature of the application, it was fundamental to ensure that users could navigate seamlessly, interact with the tools at their disposal, and be able to extrapolate information from our work without any major complications. Secondly, the tests will also serve to gauge whether the application serves the purpose of functioning as a tool that facilitates dam inspection and monitoring. Thus, we aimed to gauge its competency in executing these tasks. By effectively simulating the scenario of the Cabril Dam, we aimed to make "ImmersiVizDam" not just an immersive experience but also a robust tool that meets the needs of dam engineers and technicians.

To ensure that our work would be practical in real-world scenarios, our user tests were conducted on staff from LNEC, who are directly involved in dam monitoring and inspection tasks on a daily basis. Their expertise and knowledge were incredibly helpful in our evaluation. Given their firsthand experience and understanding of dam inspection complexities, their feedback was invaluable to our findings. While it offered insights into the application's current performance, it also highlighted potential changes that could improve the immersive experience of our application. By hearing and noting their recommendations and observations, we were able to get a good understanding of areas that need some improvements and possible new features that could help the task of dam monitoring.

Here are the steps of each test session:

- Welcome the user and brief introduction.
- Filling out of a consent form by the user.
- Filling out of a user characterization form by the user.

- Brief presentation of our work by showing the user a demonstrative video of our application that highlights its functionalities.
- Ten minutes trial to experiment with the application.
- Realization of four tasks by the user, each focusing on a different area of the application.
- Filling out by the user of a feedback form so that we are able to register its sentiment about this experience.

All the tests were conducted individually by each user, with the author of this application performing the duties of both observing the user's behavior and guiding them throughout the tests.

Depending on the user's response to the consent form, we captured photos and videos to demonstrate our tests for this work.

The tasks chosen to illustrate the potential of our application were chosen directly with the help of LNEC staff. These tasks were chosen to represent all the different modes of our work and to demonstrate the application's practicality in performing day-to-day tasks often done by dam engineers and technicians.

The first task was presented as follows:

Determine how many geodetic marks are represented in the dam wall.

Its objective is to evaluate if our representation of the sensors is clear enough for users to understand it and to gauge the user's overall understanding of this application. It required that the user use the controllers to get closer to the dam wall and then observe how many were represented, despite this, there were some users able to count the number of sensors from a considerable distance.

The second task was presented as follows:

Determine the maximum value of the observed displacements when the water level is 290 meters.

This task's objective is to assess if the accessibility to different modes of our applications was understood by users, not only that, but it also allowed us to get information on whether users could extrapolate information from the UI, which entails its readability.

The third task was presented as follows:

Determine the maximum value of the calculated displacements when the water level is 270 meters.

Once again, this task is very similar to the second task, needing the user to interact with the water level slider to get the desired water level, in order to test the UI's usability and to infer the value needed from the UI.

The final task was presented as follows:

Determine the frequency of the third vibration mode when the water level is maximum, and see the corresponding oscillation.

Much like the others, this task ensured that users could navigate through the different modes of ”ImmersiVizDam” to get to their desired menu, from there, the user only had to figure out which mode he needed to select and extrapolate the information from the UI. Finally, the user only needed to hit the play button to visualize, in real-time, the oscillation of the dam.

In order to perform these tasks, the users (Fig 6.2) would start with the application already running in the VR device, and the application started in the mode where the sensors are represented on the dam wall.

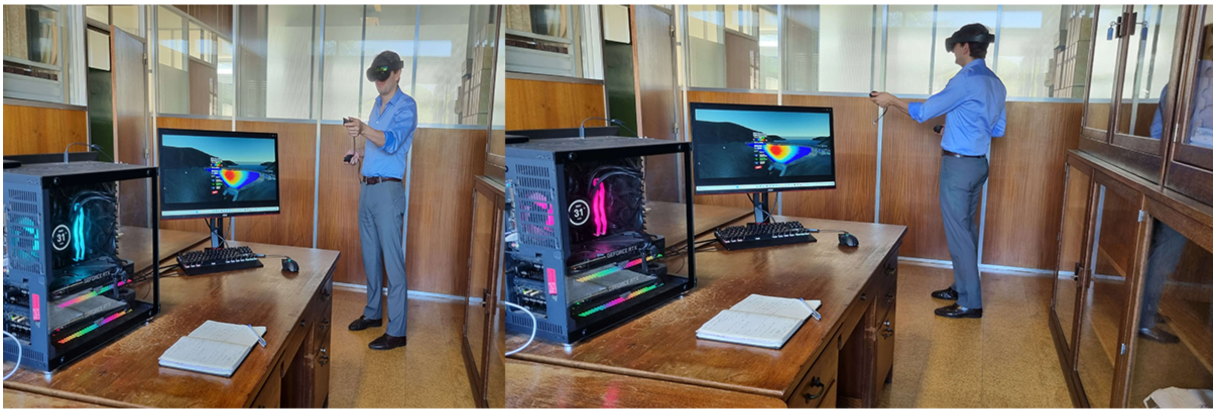


Figure 6.2: Participants interacting with ImmersiVizDam

Finally, these real-user tests allowed us to collect objective metrics such as the time needed to complete each task and the number of errors committed in each task. Through our feedback form, we were also able to collect subjective metrics:

- UI’s Friendliness.
- UI’s Accessibility.
- Perceived ease of use.
- User Satisfaction.
- Learnability.
- Task’s efficiency and difficulty.

6.1.2 User Characterization

We conducted the tests on a total of 21 users, all of whom were current workers at LNEC. The users were 78% men and 22% women, with their age depicted in Fig 6.3, and as we can see in the same figure, the vast majority of our users had a university degree, which indicates a high level of education, with more than half of our users holding a Ph.D.

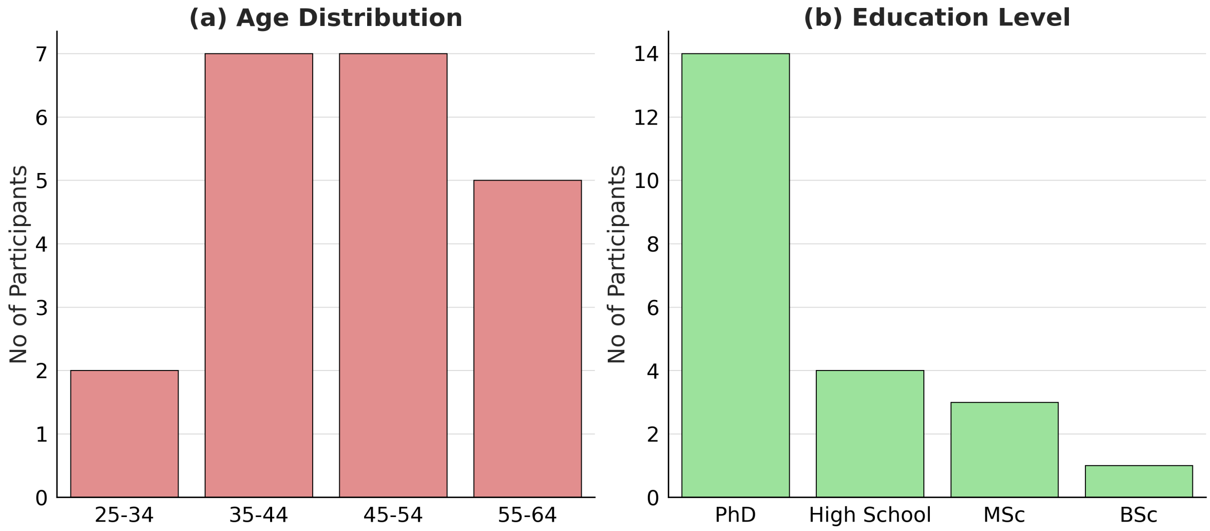


Figure 6.3: Age Distribution and Education Level

While a notable 73% of the participants have had some exposure to Virtual Reality (VR), only three individuals reported using it on a frequent basis. This highlights that the majority of our users possess limited experience with these immersive technologies. With this in mind, it would be prudent to approach deploying these tools with user-centric guidance and support (Fig 6.4).

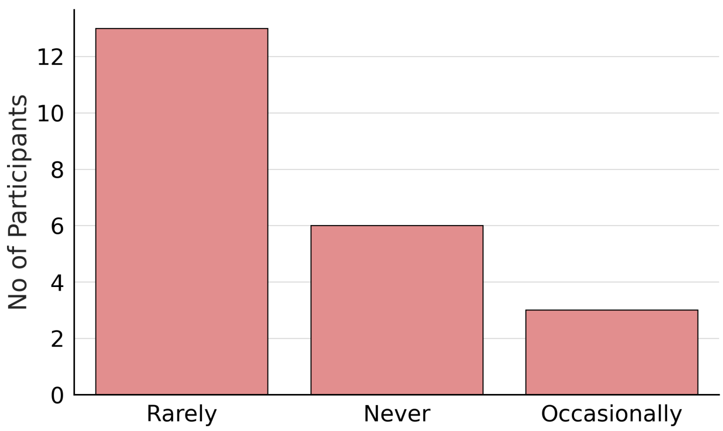


Figure 6.4: Frequency of using VR

On top of that, all of our users except for one worked professionally in the domain of dams. These users worked in different research centers like the Observation Center - NO (27%), the Applied Geodesy Center - NGA (14%), and the Modelling and Rock Mechanics Center - NMMR (36%) as depicted in Fig 6.5.

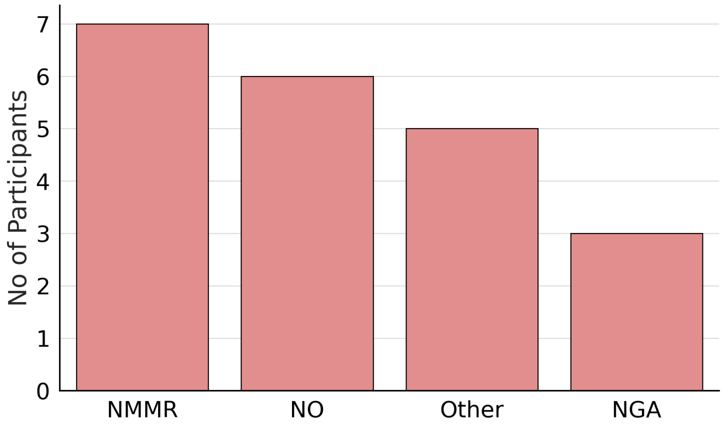


Figure 6.5: Distribution between different dam domains.

6.1.3 Results

When analyzing the objective metrics from the four tasks assigned to our users, each was successfully completed with minimal errors. These discrepancies predominantly arose in the second and third tasks, attributed primarily to some interpretation challenges with our UI. However, it's worth noting that 95% of participants completed the second task with no errors, and 86% navigated the third task flawlessly. In contrast, the remaining tasks were executed impeccably by all users. Impressively, each task was completed on average, in under 45 seconds, which highlights the small number of issues that occurred during the testing phase (Fig 6.6).

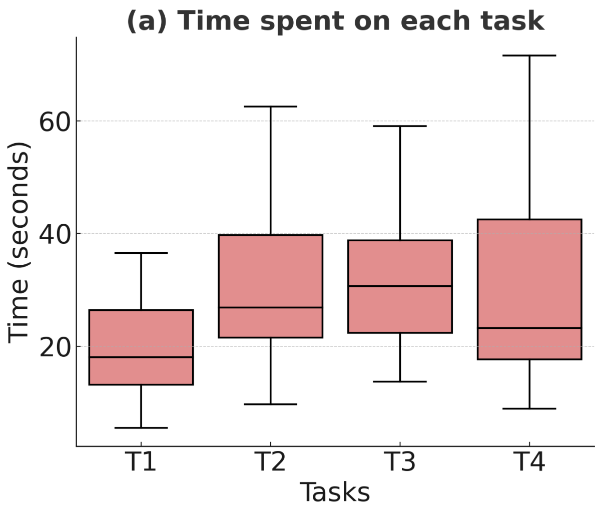


Figure 6.6: Time needed to complete each task.

At the end of performing the four tasks, the users were asked to answer feedback questionnaires that allowed us to gather subjective metrics about our prototype and the test that they had just finished. This questionnaire used questions to be rated by the user on a scale from 1 (less favorable) to 5 (more

	Average	Median	IQR
General			
Ease of learning prototype?	4.7	5.0	0.00
Ease of finding functionalities?	4.6	5.0	0.75
Clear prototype feedback?	4.6	5.0	0.75
Navigation intuitiveness rating?	4.4	5.0	1.00
Feelings on prototype design?	4.6	5.0	1.00
Was the prototype efficient for tasks?	4.7	5.0	0.00
Recommend prototype for similar tasks?	4.6	5.0	1.00
Did the prototype meet ease-of-use expectations?	4.6	5.0	0.00
Task 1			
Ease of completing	4.6	5.0	0.0
Efficiency feeling	4.6	5.0	0.0
Clarity	4.9	5.0	0.0
Satisfaction	4.5	5.0	0.0
Task 2			
Ease of completing	4.7	5.0	0.0
Efficiency feeling	4.6	5.0	0.0
Clarity	4.8	5.0	0.0
Satisfaction	4.8	5.0	0.0
Task 3			
Ease of completing	4.7	5.0	0.0
Efficiency feeling	4.6	5.0	0.0
Clarity	4.7	5.0	0.0
Satisfaction	4.7	5.0	0.0
Task 4			
Ease of completing	4.7	5.0	0.0
Efficiency feeling	4.6	5.0	0.0
Clarity	4.8	5.0	0.0
Satisfaction	4.8	5.0	0.0

Table 6.1: Feedback from the questionnaires

favorable).

In assessing the prototype, users found it straightforward to learn. Specifically, 77.3% of users rated it a 5 in terms of ease of learning, while 18.2% gave it a 4. When it came to the ease of finding functionalities, 72.7% of participants rated it a 5, and 18.2% rated it a 4. For the clarity of the prototype's feedback, the ratings were identical: 72.7% of users gave a 5, and 18.2% opted for a 4. The intuitiveness of navigation received a slightly more varied response, with 54.5% of users rating it a 5 and a substantial 36.4% rating it a 4.

For the specific tasks within the prototype, users found Task 1 to be relatively easy, with 86.4% rating it a 5 for ease of completion and a mere 4.5% rating it a 4. The same percentages held true for Task 2, Task 3, and Task 4—each saw 86.4% of users rating them a 5 in terms of ease, while 4.5% rated them a 4.

Furthermore, participants expressed their feelings vocally, regarding the design of the prototype. Other metrics were also evaluated, including the efficiency of our work for tasks and whether users would recommend the prototype to other engineers and technicians with the same tasks. This feedback provided a clear picture of user sentiment, which emphasizes areas where the prototype may excel and areas where there might be room for improvement.

Beyond the specific metrics, the overall design of the prototype was well-received by our users, which further illustrates our user-centered design approach. The efficiency with which users were able to complete the tasks further proves our prototype's effectiveness in its role. The strong showing of users to recommend the prototype for similar tasks amplifies its perceived value. This feedback, while it encompasses both specific tasks and broader design elements, shows that the prototype, despite being a first step, has potential and room for improvement to be a useful tool.

6.1.4 Discussion

In the user tests carried out, the main goal was to assess the usability of our UI and determine the suitability of our prototype in facilitating tasks performed during the process of dam monitoring and inspection. Overall, the results of these tests were successful in highlighting the potential and utility of this immersive experience in the dam domain. Moreover, feedback from participants reached an important consensus: while the prototype showcases potential, there remains considerable room for enhancement.

The efficiency with which the users completed the tasks given to them was noteworthy, with all tasks being completed relatively quickly, in our prototype. Moreover, only a few errors were recorded throughout the testing phase. This performance could potentially be attributed to the fact that our users, which consisted of dam experts from LNEC, possess substantial knowledge in this domain. Their dam knowledge might have played a fundamental role in facilitating that the tasks were performed quickly and with barely any errors, which highlights the importance of considering the user's background and expertise when interpreting our results.

In the feedback from our users, the UI stood out for its simplicity and ease of navigation, which contributed to its friendliness. This welcoming interface was complemented by the interaction from the users which was able to create interesting visualizations. The combination of these features highlights the successful integration of design and functionality that we wanted with this prototype.

Feedback directly collected during the user tests focused on specific areas of potential refinement. A recurring suggestion was the need for a way that allows users to toggle on and off the observed displacements when viewing the calculated displacements. Furthermore, some users reported that they would like to have a more effective method to compare observed and calculated displacements, with many revealing a preference for a direct numerical comparison.

Continuing with things noted by our users, specific insights emerged concerning the visualization of the modes of vibration. Some proposed that when the dam mesh oscillation is toggled off, the dam mesh should effectively represent the peak oscillation corresponding to the selected mode. Additionally, within this mode, a feature to switch seamlessly between the wireframe view and the 3D model of the dam was highlighted as something that would improve the user experience.

In addition to the feedback mentioned above, users quickly spotted some specific concerns related to the display of our interface. There were occasional instances where the users reported a slight shaking in the UI, which, upon inspection, might be attributed to an issue inherent to the Meta Quest Pro. The pointer coming from the VR controller was another area where improvements could be made. Furthermore, even though the application presents plenty of features, users felt that the movement controls necessitate some time to get used to. Addressing these concerns would improve the user experience in future iterations, and elevate this prototype to a new level.

7 Conclusions

As we draw conclusions, it's fundamental to remember the main goal of this project: the exploration of Extended Reality technologies, more specifically Virtual Reality (VR), in the realm of dam inspection and monitoring. This work explored the different possibilities and intricacies of using immersive analytics to enhance and revolutionize the traditional methods of dam monitoring and inspection, finding many insights with potential and challenges that may arise when trying to merge these cutting-edge technologies with critical infrastructure monitoring.

To support our research, ImmersiVizDam was created and evaluated and is designed to operate seamlessly on a VR device, allowing users to fully immerse themselves into a detailed, interactive environment that suits the tasks of dam inspection. The application's functionalities extend from stunning data visualizations, ranging from the placement of geodetic marks to observed and calculated displacements, as well as different modes of vibrations. This depth of data representation proves to be vital for professionals needing comprehensive overviews and insights into dam structures.

A defining feature of ImmersiVizDam is its ability to superimpose a mesh, which is similar to the dam's structure, onto the actual 3D model of the dam. This superimposition facilitates comparisons, enabling users to juxtapose expected finite element numerical models with tangible realities such as the displacements generated from geodetic marks, enhancing their ability to identify areas that may need intervention.

7.1 Achievements

A standout accomplishment of this research is the demonstration of the feasibility of XR technologies for dam inspection and monitoring activities. By assessing that these newer technologies could be revolutionary in this specialized domain, we've highlighted the path to be followed for modernizing and enhancing the methodologies used by dam engineers and technicians.

Another significant achievement was the application's simple design and navigation, which made it so that users with no prior VR experience, were able to adapt and explore the application effortlessly. The UI was developed to ensure simple navigation and interactivity, which was especially appreciated by our users. Furthermore, the positive feedback from LNEC, expressing satisfaction with how the requirements were addressed and met by our application, underscored its practicality and effectiveness in being the first prototype for a future full-fledged application.

Lastly, during the journey of the development of ImmersiVizDam, we were presented with numerous challenges, making our relative success all the more rewarding. Tackling issues inherent to our inexperience with the chosen technologies, going above and beyond to understand to compensate for the lack of documentation in some areas, and navigating the struggles that often emerge when delving into VR development for the first time were among the primary obstacles. Additionally, the need to integrate different datasets and obtain real-time performance optimization in an immersive environment added obvious complications. Despite all of that, our ability to overcome these challenges not only showcased our resilience and adaptability but also cemented the effectiveness of the ImmersiVizDam application.

7.2 Future Work

Even though the journey from the conceptualization, to the development and evaluation of ImmersiVizDam was immensely rewarding, the nature of technology, successful design approach, and results from the evaluation suggest that there's room for refinement. Regardless of our success in creating a pioneer VR application for dam inspection and monitoring, the always-evolving nature of VR methodology, coupled with the intricacies of dam monitoring tasks and needs, indicates some areas where we could improve our work. As we look into future work, it's evident that while significant developments were made, there are some aspects to further tune and optimize for a definitive VR application to be used in dam monitoring and inspection.

A primary path for future enhancement can be centered around the representation of more sensors within ImmersiVizDam. A final VR application should dynamically evolve to incorporate a bigger paradigm regarding these sensors. Additionally, while the immersive environment of the Cabril Dam offers a unique visualization experience to our users, there's undeniable value in integrating 2D visualizations along with the current immersive visualizations. Such visualizations would offer more clarity and simplicity for specific tasks and allow users for a comparative to what would be expected in desktop-based approaches.

Furthermore, incorporating different and new visualizations within our work could improve and elevate the user experience to a new level. By introducing different visualization paradigms, users would be able to select the visualization that better fits their specific tasks, enhancing its understanding and efficiency. Another promising enhancement lies in the integration of new and diverse data collected in the sensors currently placed at the Cabril. These sensors are becoming more advanced at each passing day, and utilizing their full potential by visualizing their corresponding data in helpful visualizations is fundamental for the application to remain at the cutting edge of dam inspection technology.

An essential upgrade for ImmersiVizDam is related to the way data is loaded. Shifting from static sources, as we are currently using, to integrating real-time data from LNEC's databases would deeply amplify the application's usability. Providing dam engineers and technicians with immediate access to the latest data would ensure that they were able to promptly decide and act in case of a malfunction at the dam, which ensures timely responses and further enhances the importance of our work in dam inspection and monitoring.

Looking ahead, AR also offers intriguing potential for our application and its uses. Using the VR device's passthrough mode, we could potentially blend this virtual environment with the real world, enhancing collaboration among dam technicians and engineers. This would allow for a collaboration that could facilitate real-time discussions and collective decision-making. Despite this work being a pioneer for the development of a final prototype for dam inspection and monitoring, we believe that all of these improvements could be of substantial importance.

7.3 Final Remarks

As we reflect upon this work, it's necessary to acknowledge the significance of our efforts while developing ImmersiVizDam. Even though the presented application stands as a first prototype, its successful execution and evaluation highlight a crucial message: Extend Reality technologies possess a high degree of applicability within the dam domain. This work, while preliminary, serves as a beacon, which tends to illuminate the revolutionary potential of integrating state-of-the-art solutions into fields mainly predominated by traditional approaches, with the promise of further innovations on the horizon.

With each passing day, new advancements are being made in XR technologies, and new features continue to emerge, enhancing their precision, utility, and accessibility. These continuous improvements and new features further justify our assertion about the potential of said technologies in the dam domain, reinforcing our message and vision for the future.

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