dam world 2020
Fourth International
Dam World Conference
PORTUGAL • LISBON • LNEC • September 21-25, 2020

EXTENDED REALITY IN THE SAFETY CONTROL OF DAMS

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ABSTRACT

Dam Safety Control has been at the front line of technology adoption in what concerns data acquisition. However, it does not take full advantage of the latest advancements when it comes to in-situ, real-time, information visualization. This work explores the application of Augmented Reality to the inspection and monitoring of large Civil Engineering structures, namely concrete dams. The proposed approach focuses on offering new visualization possibilities, that are not accessible through traditional means, to Dam Safety Control. In that scope, it depicts the specification and development of a proof-of-concept prototype that allows the monitoring of relevant structural-related information in an Augmented Reality environment. In particular, it offers an easy and straightforward way for Civil Engineers and Observation Technicians a mean to access data from the network of sensors situated in the downstream face and the interior of the structure. Besides providing insightful information on the current status, it allows exploring the evolution in time of values registered in each sensor. A preliminary study aimed at validating the proposed approach shows that Augmented Reality technologies can be used efficiently in Dam Safety Control.

Keywords: dam safety control, extended reality, augmented reality, structural health monitoring, concrete dams

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1. INTRODUCTION

Extended Reality (XR) refers to the set of real-and-virtual combined environments such as Augmented Reality (AR) and Virtual Reality (VR). The XR spectrum has been conceptualized by Milgram (1) in the reality–virtuality continuum, which encompasses all possible variations of real and virtual objects (Fig. 1).

Fig. 1 – Reality–virtuality continuum (1)

While VR allows for users to be separated from reality and immersed in a simulated experience, AR can augment the user experience, by superimposing virtual elements to the real world.

XR technologies have had considerable growth in popularity in recent years. This growth has been in part due to the evolution of VR and AR techniques. More capable software, application program interfaces, and tracking methods have been developed. We have also seen significant advances in the latest generations of dedicated XR hardware.

These advances include an increase in the definition and overall quality of cameras and sensors. The growth in speed and efficiency of graphical processors (2) has also been decisive. Another critical factor has been the price cut occurred in hardware. As a result, XR technologies have had the opportunity to be tested, even in areas where the use of traditional visualization techniques has been long-established.

In what regards AR, applications have been developed in a multitude of scenarios and with distinct purposes, to provide relevant real-time information that enhances the interaction with the real world. The practical use of AR has long exceeded the scope of entertainment and is progressively being introduced to the professional environment, namely in medicine, military, and tourism.

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

This work explores the use of AR technologies in large structures and examines its role in the safety control of dams. It analyses and evaluates the feasibility of efficiently applying AR technologies in a dam safety control scenario. In that sense, it is focused on the opportunity of creating new observation paradigms by offering visualization possibilities that would not be accessible using traditional tools. In that scope, is also addresses the design and development of "DamAR", a prototype that can aid dam inspectors in the structural inspection of dams.

Apart from this introduction, this work presents, in Section 2, related work concerning the use of extended reality technologies in the AEC area. In Section 3 an XR application to the safety control of dams is described, including the proposed requirements, the approach taken and the evaluation. Finally, in Section 4, the conclusions concerning this work are presented.

2. EXTENDED REALITY IN AEC

The AEC sector has been on the front-line in what concerns the early adoption of emerging and innovative technologies (2). In that sense, XR applications have been developed for architectural design, urban planning, construction management, or structural health monitoring, among others.

Regarding the visual inspection of large Civil Engineering structures, Veronez et al. (3) created "Imspector", an immersive system for the inspection of bridges and viaducts. The system uses mapping data gathered by Unmanned Aerial Vehicles (UAVs), using laser scanning, to generate 3D models that can be integrated into virtual environments. These immersive environments can be explored by the Structural Engineer or Inspection Technician using VR headsets. Such systems allow the inspection itself to be made off-site, by specialized professionals, while the gathering of data can be handled on-site by less specialized staff. The use of VR in this case also has the potential of hindering one of the main difficulties when inspecting large structures, which is the difficulty in physically accessing specific locations (4).

BIM has been a constant buzzword in the AEC sector in the last decade. In the context of BIM, Raimbaud et al. (5) created a way of adapting BIM data to be used in virtual environments. The devised methodology uses filtering techniques to select which segments of the BIM raw data are useful for creating 3D elements for VR visualizations. The filtering is based on the role of the user in the construction project. It is also based on the subset of BIM data that he wants to visualize. This type of 3D visualization has been shown to increase the participation of users in the design process, when compared to traditional visualization (6).

Raimbaud et al. (7) also addressed the use of AR to verify the accuracy of construction. They developed a system that allows a Civil or Structural Engineer to compare what has been effectively built in the construction site with what was originally planned in the project. This comparison is made in an AR environment, by superimposing BIM models with real images captured by UAVs. The system also allows the user to make annotations regarding the differences detected, which can later be used to either make corrections in the construction site or alter the BIM model.

In the area of Traffic Engineering, Uhr et al. (8) built a decision support system for traffic planning that uses a hybrid VR setup. The system combines different interactive display technologies, including an interactive tabletop and a Cave Automatic Virtual Environment (CAVE) projection. In coordination meetings, engineers can collaboratively plan traffic interventions around the touch tabletop. As they select a specific road or intersection for analysis, the CAVE displays 360º real-world images of the location being analyzed. The system provides an immersive environment that tries to replace visiting sites in person, which is time-consuming and expensive. Veronez et al. (9) developed a VR system to assist Civil Engineers in road design. By using a VR headset and a steering wheel for PC, the designer can assess how driving through a projected road section will feel. The solutions' primary objective is to provide, in the design phase, an assessment of the driver's predictable perception and behavior. With such an evaluation, the designer can refine its solution for the road section to be safer and more comfortable to drive.

In the scope of municipal infrastructure works, Côté et al. (10) developed an AR method for the augmentation of subsurface utility pipes. While this type of solution, which allows the user to have a kind of "X-ray vision" of what is under his feet, has been extensively studied in the past (11) (12) (13), this new method promises increased accuracy.

The authors propose the use of pre-captured photorealistic 3D meshes of the roads, as a reference for the alignment of the pipe network. This reference prevents misalignment problems, where the pipes appear to float above the road, due to variable topography. The technique includes an intermediary step where the subsurface utility 2D map is manually aligned with the photorealistic mesh. This step is achieved by taking into account visual clues, like maintenance hole covers, hydrants, or drains.

Ergün et al. (14)explored the use of VR and AR, together with already-existing design tools for Architecture. They developed a process that allows the seamless integration between BIM tools and 3D graphical engines typically used for XR visualizations.

Such a process fosters a continuous bidirectional workflow that allows the expansion of the capabilities of BIM. In that sense, the Architect can make changes in a projects' BIM data and then analyze the results in an immersive environment that simulates the implementation of the project in real life. On the other hand, he can make adjustments directly to the 3D VR model, and those adjustments will be passed automatically to the BIM database.

Boustila et al. (15) studied the way that distances are perceived in virtual environments, in an architectural framework. They analyzed how the cognitive profile of the user, the furnishing of a building, and locomotion speed can affect distance perception. Based on the results, they present guidelines for setting up architectural project review tools.

In the scope of architectural project review, Boustila et al. (16) studied the perception of the near surrounding ground in virtual environments. By increasing the vertical field of view, using a hybrid projection of the floor, they were able to improve the perception of nearby objects without degrading the understanding of distances and volumes.

Kán et al. (17) devised a method for automatic interior design using VR environments. A procedural approach was used, which allows a fast generation of furniture arrangements in interior scenes. The process is suitable for generating large-scale indoor virtual environments. Moraes et al. (18) focused on the automation of 3D modeling for integration in virtual environments. By using a modular approach, they were able to optimize the scene creation process and accelerate the generation of 3D models of hydroelectric power plants.

In the framework of urban projects, Vigier et al. (19) studied climate perception in virtual urban environments.

They focused on the role of visual cues, like the features of the sky, shadows, the location of the sun, and the characteristics of light in the user perception of seasons, time of day, and temperature. Such aspects are particularly important, as VR has grown to be an essential tool for Urban Designers in the design and assessment of urban projects.

VR has also been used in the context of occupational health and safety. Di Loreto et al. (20) created "WoaH", a VR work-at-height simulator. The system can be used for training workers in work-at-height engineering operations, like the construction or inspection of bridges, high-rise buildings, or dams. WoaH uses an HMD together with a real ladder synchronized in position with a virtual one in the VR environment. By simulating that the user is suspended at a great height, the VR solution can be employed in detecting if trainees are susceptible to vertigo and are able to manage stress when working at height. Chardonnet et al. (21), on the other hand, devised a VR system to detect Acrophobia (the irrational fear of heights) in work-at-height situations. The solution subjects the user to a high fidelity VR simulation that triggers the fear of heights. The simulation includes both static haptic feedback and vibrations.

Nickeletal. (22) created a VR simulation for occupational safety and health assessment during hydraulic machinery design. The system simulates the operation of river locks and is intended for use by risk assessment inspectors. Moving through the virtual lock, they can determine the safety hazards, risks, and requirements before the river locks are effectively built. The contextualization of construction accident reports was addressed by Peña et al. (23).The system allows users to explore a construction site, in a VR environment and interact, and learn more about a particular accident. Shaw et al. (24) built a VR setup for the fire safety assessment of buildings. They associated the traditional audiovisual (ADV) experience provided by an HMD to thermal and olfactory stimuli. Fire is simulated by a regulable intensity infrared heater that turns on when the user is in the proximity of flames in the virtual environment. The smell is simulated using a dedicated scent dispenser with a dispersion fan. These additional stimuli allow a more immersive experience that can better capture user behavior in a set of a fire evacuation.

3. EXTENDED REALITY IN THE SAFETY CONTROL OF DAMS

In the framework of a cooperation between the Instituto Superior Técnico at the University of Lisbon and the Department of Concrete Dams (DBB) of the Portuguese National Laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil, LNEC) we explored the use of AR technologies in the safety control of dams. In that scope, a prototype was development that has the objective of aiding dam inspectors in the structural inspection of dams. The system allows the superimposition to the user’s view of the real world, of relevant 3D information concerning the positioning and geometry of the network of sensors located inside the structure of dams and along its downstream face, as well as the visualization of structural monitoring data. This prototype runs on a tablet but was developed to be easily adaptable to dedicated AR Head Mounted Displays (HMD’s).

The DBB at LNEC is responsible for monitoring the behavior and controlling the structural safety of 70 of the largest concrete and masonry dams in Portugal (25). The Cabril dam (Fig. 2) was used as a case study. This double curvature concrete arch dam was built in 1953 and is located in the Zêzere river, on the border between the counties of Pedrógão Grande and Sertã (26). The structure has a crest length of 290 m, and the central console has a thickness that varies between 4.5 and 19 m (26).

(a) General view (b) Downstream face of the structure

Fig. 2 – Cabril Dam

On the downstream base of the dam, there is a hydropower plant and two semi-hidden tunnel spillway outputs, one in each riverbank. It is considered the highest arch dam in Portugal, with a height of 132 m (27) and was suggested by LNEC as an ideal candidate for the validation of the application.

The Cabril dam includes several sets of sensors and other devices. These are used for the monitoring of the upstream and downstream water levels as well as vertical and horizontal displacements both in the structure and in the foundation. The dam also incorporates sensors to measure relative movements in joints and cracks, temperatures of the air, the concrete and the foundation, extensions in the concrete, foundation uplift, drained (inflow) and infiltrated flows and dynamic accelerations (26).

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

- using geodetic methods (26), namely through exterior triangulation employing a network of fixed marks installed in the downstream face of the dam;

- through 10 plumb lines (26) installed in vertical holes in the interior of the dam structure (Fig. 3);

- by means of global navigation satellite systems (GNSS) equipment, using two receivers installed in the central point of the top of the dam and the outskirts of the dam respectively. This process is used solely as a reference station (28).

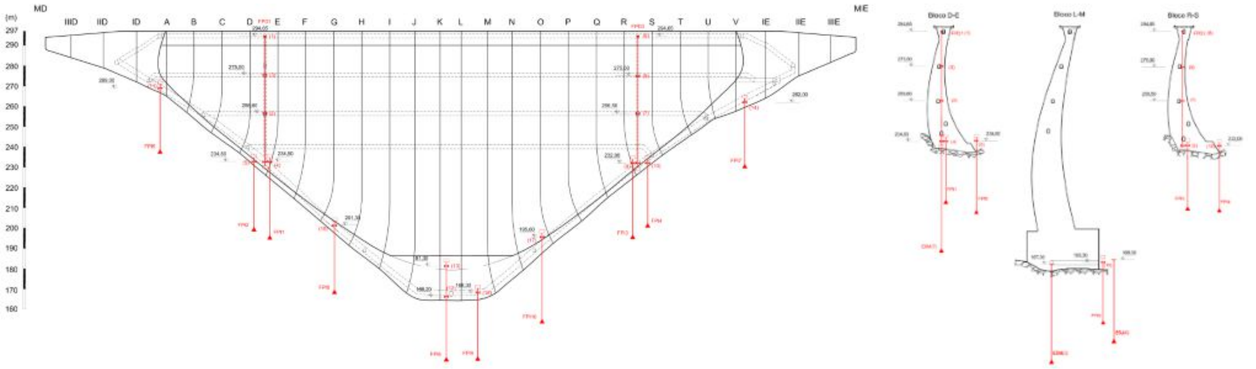


Fig. 3 – Location of plumblines in the interior of Cabril Dam (Image: LNEC)

3.1. Requirements

LNEC proposed the development of an AR system that would facilitate the identification of the location of the different sensors and measuring devices aimed at the determination of horizontal displacements in the structure of the dam.

The system would offer LNEC technical staff, the dam owner and the others involved in periodic inspection visits, more intuitive perception of the distribution of the monitoring devices network. In addition, LNEC suggested the inclusion in the system, of other functionalities, namely the possibility of graphical visualization of the evolution of displacement values registered by the sensors.

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

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

- the possibility of selecting a specific sensor and viewing the evolution of the displacements and other relevant values, pertaining to that sensor.

The prototype was designed to be used by the technical staff involved in the inspection and monitoring of the Cabril dam. These include experienced structural engineers that can use the application to visualize in-situ the evolution of dimensional/structural parameters and, observation technicians that can use the application, for example to locate a specific sensor quickly inside the dam during the inspection campaigns.

The users are not necessarily highly skilled technologically, and therefore the system was designed with a simple and straightforward user interface (UI). They also had been using the same processes and methodologies for many years, so seamless integration of the technology with the established workflow, was fundamental. That meant, for example, maintaining the existing symbolic and naming conventions. Furthermore, it was agreed that the prototype should be directed at the observation of the dam from a downstream position.

This position allows the observer to have the most favourable view of the location of the network of sensors. The observation of the dam from the inside of the galleries, using AR, was left for future work.

LNEC pointed out that the values of the horizontal displacements and their evolution with the air temperature and upstream water level as the most relevant data for the scope of this work. In that context, the system was focused on the visualization of horizontal displacement data obtained through three types of devices: geodetic marks; plumb lines; and, GNSS.

3.2. Approach

The prototype was developed with the objective of understanding if AR technologies could effectively be used in relevant tasks related to Dam Safety Control. The AR application consists of four main components that work together to transform the structural monitoring data into useful augmented visualizations (Fig. 4). The first component is the Data API, which allows the AR App to load and parse information from the data files provided by LNEC. The information flows via the Data API, to a second component, the Interaction Module. This component serves as a bridge between the structural monitoring information, and the other two remaining components: the AR Software Development Kit (SDK) and the 3D graphical engine (Vis Module). The AR SDK is responsible for providing object recognition and tracking to the system. The Vis Module, on the other hand, is used to render 3D models in the AR scene and produce the final visualizations.

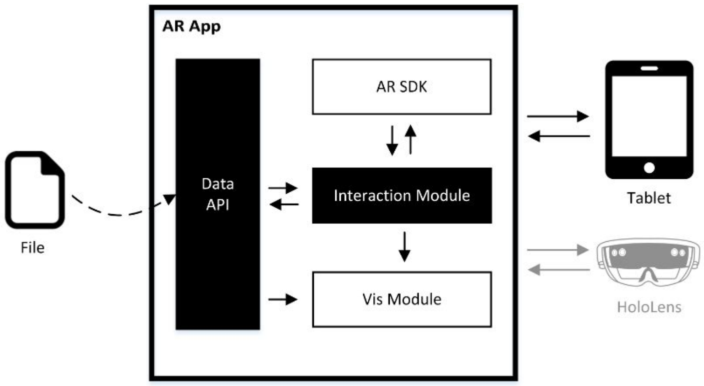


Fig. 4 – System architecture

The UI allows for the structural inspectors to visualize, superimposed to the real structure, different types of information relevant to its tasks (Fig. 5). Because the hardware platform for the testing of the prototype was an Android tablet, the interaction of the user with the system is done using touch.

Fig. 5 – General view of the UI

The UI includes a set of toolbars and menus. These allow the user to easily navigate through the different AR visualization options and horizontal displacements information (Fig. 6).

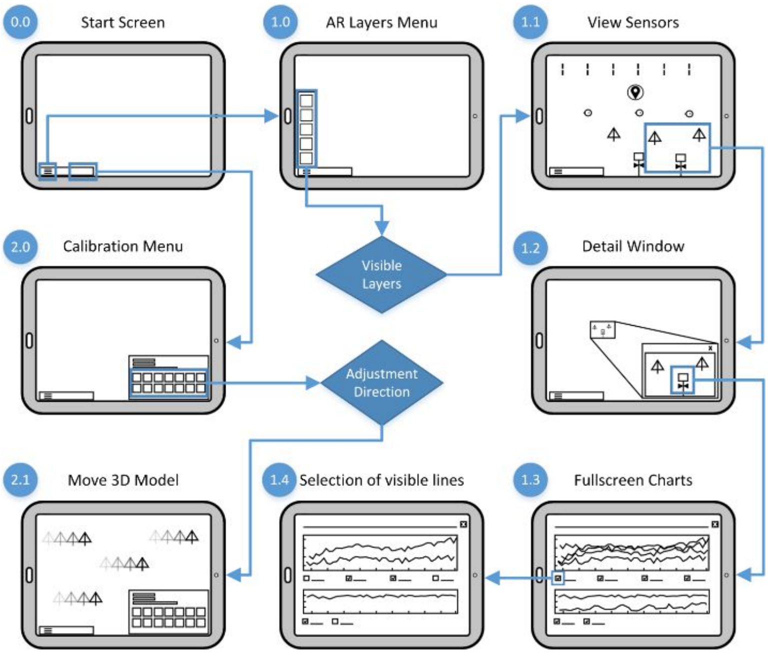


Fig. 6 – UI flow diagram

In the start screen, the user is presented with a small toolbar situated in the bottom-left corner. If the user taps the menu symbol situated in the leftmost area of the toolbar, the AR Layers Menu is shown (Fig.7 a)). This menu allows the user to control which visual elements will be shown in the AR environment (Fig.7 b)). By selecting these buttons, the user can show or hide the different layers.

(a) Menu that allows the user to select which visual elements should be shown in the AR environment.

(b) Network of sensors in the AR environment

Fig. 7 - Controlling visual elements in the AR environment

The first three buttons (from bottom to top) correspond to the primary sensors for measuring horizontal displacements: geodetic marks, plumblines, and the GNSS antenna (Fig.8). The top button allows for an auxiliary mesh to be shown, which represents the location and designation of the constructive joints of the Cabril Dam and a vertical altitude scale. LNEC staff typically uses the nomenclature of these joints when referring to a specific area of the downstream face.

(a) Geodetic marks

(b) Plumblines

(c) GNSS

Fig. 8 - The three types of horizontal displacements sensors/devices that can be represented in the AR environment

Additionally, the AR Layers Menu includes a displacement vectors option, directed at the visualization of displacement vectors superimposed to the dam. This functionality allows for the magnitudes of displacements to be visualized directly in the AR environment. Depending on the layers selected, the AR environment is populated with a set of sensors and devices that can be selected in order to obtain further information regarding a specific sensor.

When the sensors are situated too close to each other in the sensor network or the observer is positioned too far away from the dam, the selection of a specific sensor is difficult. In fact, in certain conditions, the sensors appear almost superimposed, making the proper selection virtually impossible. For the precise selection of individual sensors, even in very "crowded" areas, a detail window that shows a zoomed view of a specific region of the network of sensors (Fig.9) was implemented. So, instead of worrying about selecting a particular sensor in the network, the user can tap the region surrounding the location of the desired sensor. The detail window then appears, by default in the bottom-right corner of the screen, where the sensor can be selected with precision.

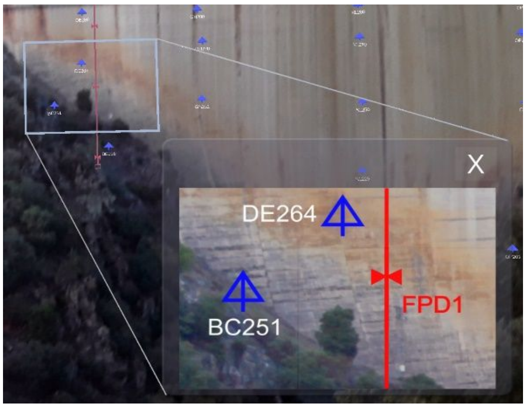
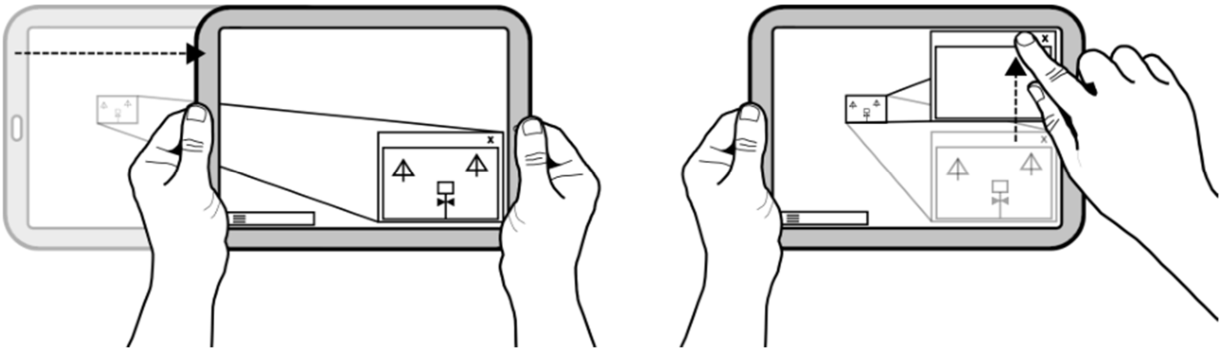


Fig. 9. Detail window.

Furthermore, the selected area is highlighted, in the network itself, by a rectangular contour. The contour is attached to the detail window by two guidelines. These guidelines follow the movement of the tablet and allow, at all times, to establish a visual connection between the selected area and the detail window. They also remain active even when the selected area is not in the field of view (Fig.10 (a)). The position of the detail window can also be adjusted (Fig. 10 (b)).



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

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

Fig. 10 - Features of the detail window.

After the user selects the sensor on which he wants information about, a fullscreen window is displayed. This window shows the type and designation of the sensor and two line charts (Fig.11). The top chart contains the evolution of horizontal displacement values recorded over time in that sensor. The bottom chart shows the values of atmospheric temperatures and upstream water levels measured over time in the dam.

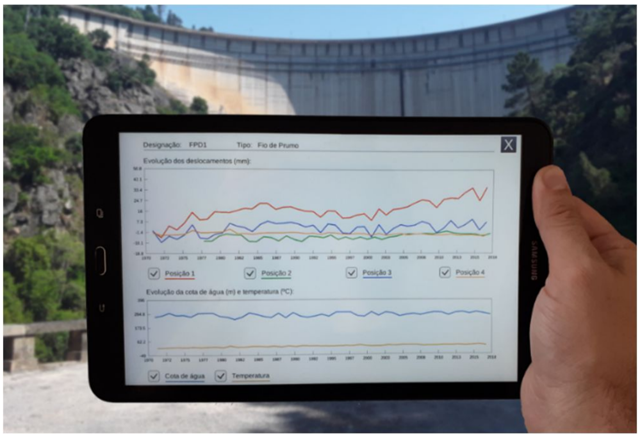


Fig. 11 - Full-screen charts representing horizontal displacements, air temperatures and upstream water levels are shown when a specific sensor is selected.

The charts are also interactive and allow the user to pan and zoom using, respectively, "pinch" and "tap and drag" movements, in order to display a specific region. To ensure that the 3D model of the network can be aligned in-situ, a special Calibration Menu was also developed. This feature allows for fine adjustments to the digital model's position in space.

3.3. Evaluation

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

The prototype performance on the real world was tested, in different points sequentially closer to the dam, along the access route that connects the National Road 2 (EN2) to the base of the dam. The successful detection of an Image Target occurred at a distance between 200 and 110 meters from the facade of the power plant. Furthermore, reasonably stable tracking is achievable at around 110 meters from the facade of the power plant, (about 150 meters from the downstream face of the dam), with a distance between the observer and the tracked Image Target, of approximately 130 meters (Fig.12). Also, at 110 meters or less, with the tablet stationary, pointed directly at the target on the left of the facade, the initial detection had a success rate of 100%, even when the lighting conditions were not optimal. The detection was also achieved almost immediately after the application had started, was operational, and the tablet was pointed at the target.

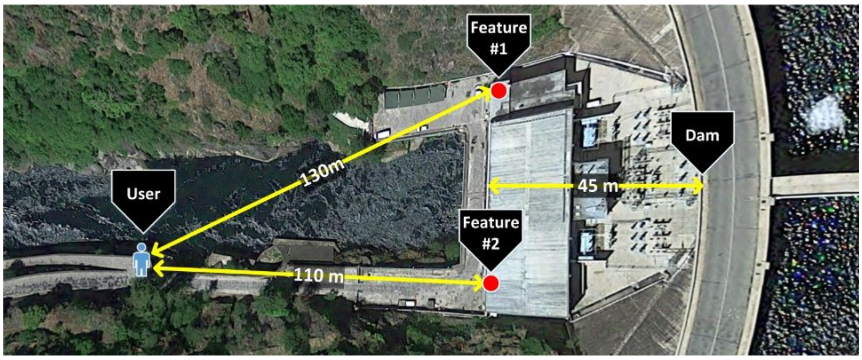


Fig. 12 - Fairly stable tracking is achievable when the user is at about 110 meters from the facade of the power plant (which is situated at around 45 meters from the downstream face of the dam), with a distance between the observer and the tracked Image Target (Feature #1), of approximately 130 meters.

Nevertheless, it was also observed that, although detection can be achieved, the stability of the tracking is very sensitive to luminosity variations and especially to the appearance of shadows. When the existing conditions in the areas of the facade of the power plant corresponding to the Image Targets were similar to the ones on the source images, the digital model had residual oscillation. However, when those conditions changed, namely, when the sun shone, and shadows covered the facade, the oscillation increased significantly, and the model moved and jumped from the initial position.

In the absence of targets inside the field of view, namely when the tablet was pointed at the upper limits of the dam structure, Vuforia' Extended Tracking (which uses the characteristics of the surrounding environment to maintain a stable tracking) took charge and allowed for the tracking to be maintained. However, a slight increase in the oscillation of the model was noticed.

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

The usability of the UI and its suitability for tasks related to the safety control of dams was assessed through real-user evaluation. The evaluation process had, as the main objective, determining the usability of the AR prototype's UI, namely its suitability for field Dam Safety

Control tasks. The evaluation consisted of real-user tests (Fig.13), using LNEC staff directly involved in the several tasks of dam observation and structural health monitoring, namely Observation Technicians and Structural/Civil Engineers, which provided first-person feedback to the system operation. This highly specialized personnel offered knowledgeable and grounded advice that was used not only to evaluate the performance of the system but also served as a gauge for the need of improvement of existing features or the introduction of new ones.

Fig. 13 - User testing the prototype

For the assessment of the prototypes' effectiveness, two tasks were chosen, together with LNEC, to be integrated into the tests. These tasks encompassed the use of relevant functionalities of the prototype and corresponded to realistic scenarios of activities that a typical user can find during its every-day work. The set of metrics registered during the tests comprised both objective and subjective measurements. The objective measurements included the time to complete tasks and the number of wrong/failed operations in each of the tasks. The subjective measurements included the global ease of use, comfort of use, visibility and ease of sensor selection, ease of use of the detail window, ease of use of the sensor selection menus, readability of the charts and suitability of the transition process between the augmented reality environment and the full-screen charts.

Regarding the objective metrics recorded during the test, all of the users completed the tasks successfully, with low completion times (less than 30 seconds). On the other hand, the number of wrong/failed operations was very low in both tasks, with 70%-80% of users performing the tasks with no errors.

In what respects the subjective metrics, these were collected through a questionnaire, where users rated the different aspects of their experience. The questions used a Likert scale between 1 (the less favorable) and 5 (the most favorable). The vast majority of the users considered the prototype to have a friendly UI (70% rated 5 and 30% rated 4), that the sensors are easy to select (60% rated 5 and 40% rated 4), have a suitable size (65% rated 5 and 30% rated 4) and use appropriate icons and colors (80% rated 5 and 20% rated 4).

4. CONCLUSIONS

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

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

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

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