DamAR: Augmented reality in dam safety control

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This paper explores the application of augmented reality to the inspection and monitoring of large structures, namely concrete dams. It proposes an approach to dam safety control, using augmented reality, focused on offering new visualization possibilities, that are not accessible using traditional methods. The specification and development of DamAR, a proof-of-concept prototype that allows the visualization, on-site, of relevant structural health monitoring information, in an augmented reality environment, is described, including the benefits to structural engineers and observation technicians. A preliminary evaluation, aimed at validating the proposed approach, shows that augmented reality technologies can be used efficiently in dam safety control.

Dam safety control has for some time been closely based on data acquisition. However, in-situ, real-time, information visualization is still lacking. Although conventional visualization solutions exist, more complex technologies, including virtual and augmented reality, have not been adequately adopted for dam safety purposes.

The architecture, engineering, and construction fields have shown an increased interest in augmented reality (AR). 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 modelling (BIM) data at construction sites, among others. AR is now also beginning to be used 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.

The Cabril dam: (a) General view; and (b) Downstream face of the structure. This dam was used as a case study in the DamAR research.

Although the SHM area has been closely associated with data acquisition, namely through the widespread use of advanced sensing technologies, there continues to be a lack of in-situ visualization of structural health information. In the observation and safety control of dams, this issue is especially pertinent because of the typically large dimensions of dams and the difficulty in physically accessing certain areas.

The task of field visual inspection, which is an essential part of dam safety control, requires that the inspector knows, among other information, the location of the various components of the dam. Among these components are several types of sensors. During the visual inspection, the inspector may need to assess both the sensor's condition and register its measured values (in cases where data logging and transmission are not automated).

Many of the technical challenges that in the past restricted the practical use of AR technologies in real-world environments, have been reduced or even surpassed. One critical issue was the inherent lack of accuracy, especially in situations where the objects of the augmented environment were a relatively long distance from the observer. This problem was tackled, in part, by the emergence of more capable AR software, application program interfaces (APIs), tracking methods and, more importantly, by significant advances in the latest generations of hardware.

Another challenge associated with the use of AR in professional applications is the transmission and processing of large data sets, often required to produce precise and useful computer-generated images and other visual information. This aspect, which is increasingly relevant in an era where 'big data' tends to be the standard not the exception, is being handled by the emergence of faster mobile telecommunication technologies. Nevertheless, to take advantage of these technological advances, the use of efficient applications which offer tangible benefits in the assistance offered to the user in the work environment, is imperative.

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. As proof of concept, the work includes the design and development of DamAR, a prototype that can aid dam inspectors in the structural inspection of dams. This prototype runs on a tablet, but was developed to be adaptable to dedicated AR head-mounted displays (HMDs). It allows the superimposition on the user's view of the real world, of relevant 3D information concerning the positioning and geometry of the network of sensors located inside the structure of dams and along its downstream face, as well as the visualization of structural monitoring data.

The work was developed in the framework of 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). The DBB at LNEC is responsible for monitoring the behaviour and controlling the structural safety of 70 of the largest concrete and masonry dams in Portugal [LNEC, 2018[1]].

The Cabril dam, see Photos (a) and (b) 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 [Pereira, 2016[2]]. The structure has a crest length of 290 m, and the central console has a thickness that varies between 4.5 and 19 m [Pereira, 2016[2]]. 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 [Oliveira *et al*., 2010[3]] 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 [Pereira, 2016[2]].

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 [Pereira, 2016[2]], namely through exterior triangulation employing a network of fixed marks installed in the downstream face of the dam;
- through 10 plumb lines [Pereira, 2016[2]] installed in vertical holes in the interior of the dam structure (see Fig. 1); and,
- 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 [Morais, 2017[4]].

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.

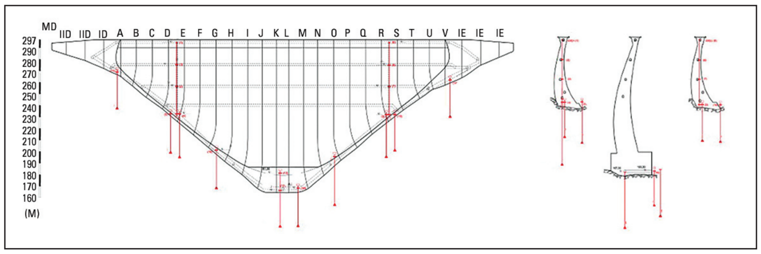


Fig. 1. Location of plumblines in the interior of Cabril dam (image source: LNEC).

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; and,
- 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.

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, as depicted in Fig. 2. The first component is the data API, which allows the AR application to load and parse information from the data files provided by LNEC. The information flows through the data API, to a second component, the inter-

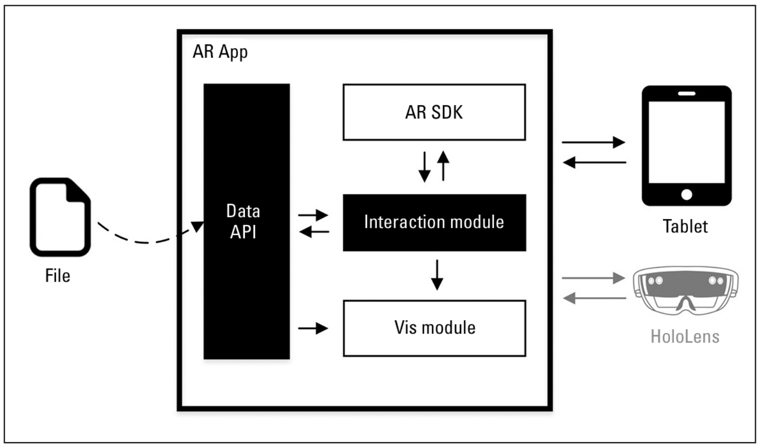


Fig. 2. System architecture.

(c) General view of the UI.

action 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.

The prototype was implemented with the widely used Unity graphical engine, as a result of its overall performance and compatibility. For the AR SDK, Vuforia was chosen. This option was, on the one hand, because of its native integration with Unity and, on the other, because of its good performance in exterior environments, as concluded by Marto *et al*. [2017[5]].

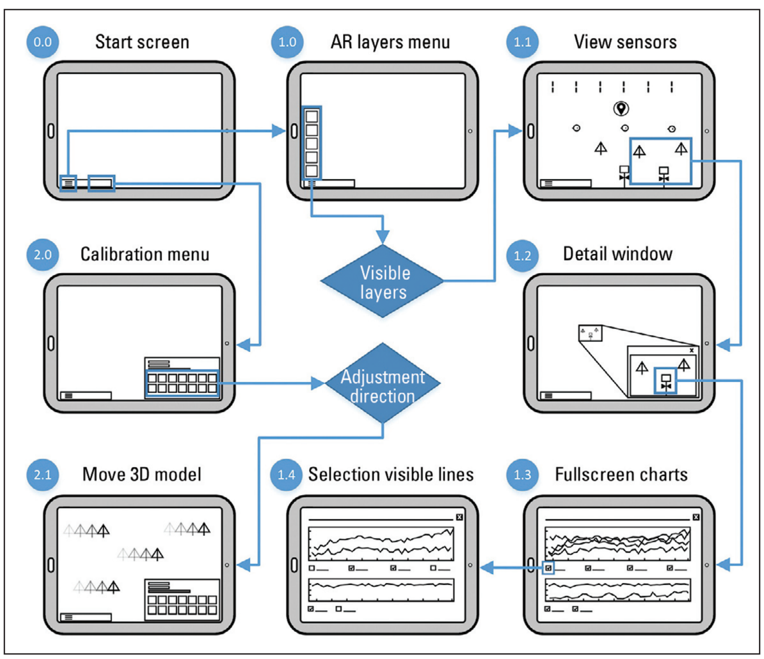


Fig. 3. UI flow diagram.

2.1 User interface

The UI allows for the structural inspectors to visualize, superimposed to the real structure, different types of information relevant to its tasks, see Photo (c). 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.

The UI includes a set of toolbars and menus. These allow the user to navigate easily through the different AR visualization options and horizontal displacements information (see Fig. 3).

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 (see Fig. 4a). This menu allows the user to control which visual elements will be shown in the AR environment (see Fig. 4b). By selecting these buttons, the user can show or hide the different layers.

The first three buttons (from bottom to top) correspond to the primary sensors for measuring horizontal displacements: geodetic marks; plumb lines; and, the GNSS antenna (see Fig. 5). 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.

In addition, the AR Layers Menu includes a displacement vectors option, directed at the visualization of displacement vectors superimposed on the dam. This functionality allows for the magnitudes of dis-

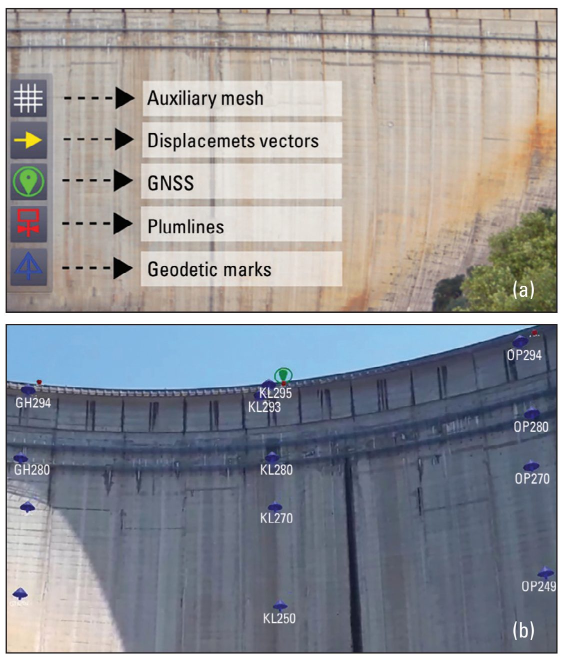


Fig. 4. Controlling visual elements in the AR environment. (a) Menu that allows the user to select which visual elements should be shown in the AR environment; and, (b) Network of sensors in the AR environment.

placements 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 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 to overlap, making an accurate selection almost impossible. For the precise selection

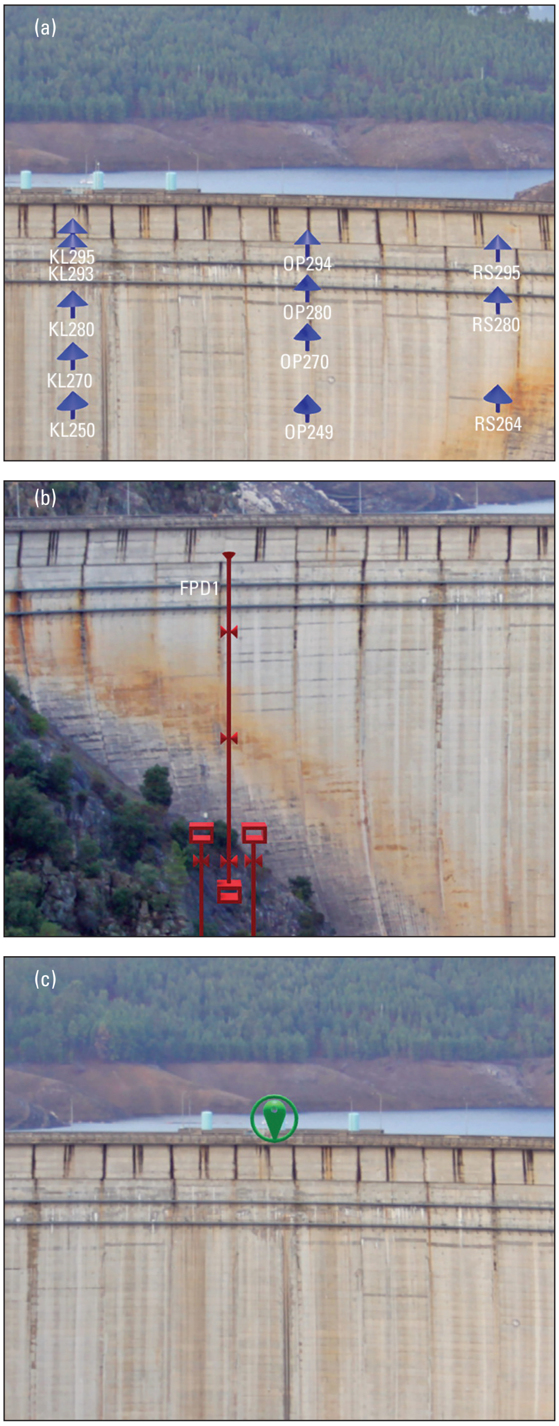


Fig. 5. The three types of horizontal displacements sensors/devices that can be represented in the AR environment (a) geodetic marks; (b) plumblines; (c) GNSS.

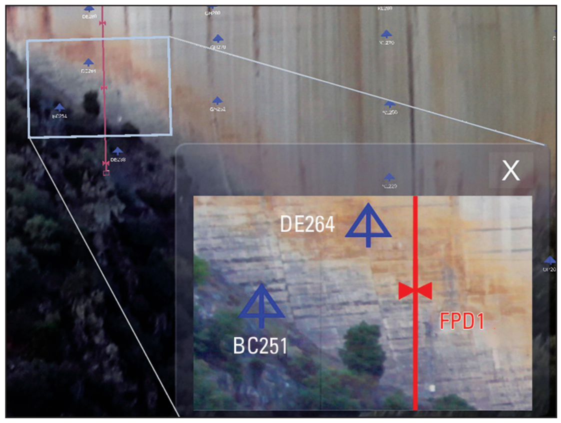


Fig. 6. Detail window.

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 (see Fig. 6) 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.

Furthermore, the selected area will be 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, a visual connection to be established between the selected area and the detail window. They also remain active even when the selected area is not in the field of view (see Fig. 7a). The position of the detail window can also be adjusted (see Fig. 7b).

After the user selects the sensor for which he wants information, a full screen window is displayed. This window shows the type and designation of the sensor and two line charts, see Photo (d). The top chart contains the evolution of horizontal displacement values recorded over time in that sensor. The bottom chart

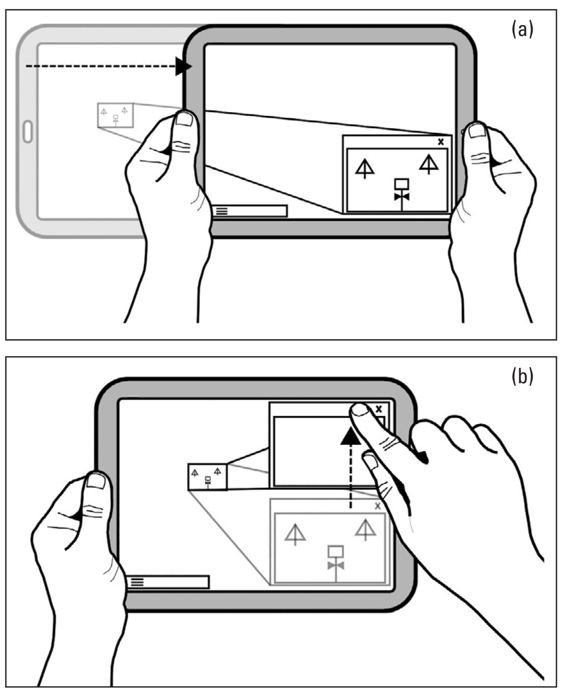


Fig. 7. Features of the detail window (a) The guidelines remain active even when the selected area is not in the field of view; and, (b) The detail window position can be changed using a tap and drag movement.

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

shows the values of atmospheric temperatures and upstream water levels measured over time in the dam.

The charts are also interactive, and allow the user to pan and zoom using, respectively, 'pinch' and 'tap and drag' movements, 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.

2.2 Calibration

To overlay the virtual 3D features to reality correctly, the application uses Vuforias' 'Image Targets' tracking technique. This technique uses pre-captured photos of the environment to recognize it. By automatically identifying key features of those photos in the image that is being visualized in the camera of the device being used (such as a tablet), the application can estimate the approximate position and orientation of the camera relative to the target. Although according to Marto *et al*. [2017[5]], the use of Image Targets does not offer the best performance as regards the stability of the digital model's position. When compared with other techniques, it is less sensitive to changes in luminosity, making it more appropriate for outside environments. Another aspect of tracking in vast exterior environments, and in particular in concrete dams, is that these are, by nature, massive monolithic structures, with regular monochrome surfaces. This superficial homogeneity is even more pronounced in the downstream face. Although some dams possess distinctive features, namely dam spillway outputs or accessory structures on the top, that is not the case of the Cabril dam. Indeed, its downstream face does not have any distinctive features that can be used for marker-less tracking (not requiring the use of traditional AR markers). To that extent, one can consider the Cabril dam type as the most unfavourable case regarding distinctive features susceptible to being used for tracking. For that reason, alternatives had to be found for AR tracking, namely the use of features of the facade of the powerplant at the base of the dam. Although not ideal, mainly because of its distance from the dam structure itself, the powerplant had a few distinctive features that allowed the marker-less tracking to take place.

To increase the probability of detection and the stability of tracking, multiple Image Targets were used. Two distinct architectural features of the facade of the powerplant were selected. For each of the architectural features, several Image Targets were created, each based on photos taken throughout the day, during field visits. These source pictures were selected based on their distinct characteristics concerning the levels of luminosity and shadow coverage (see Fig. 8).

Although the use of the application in other dams requires a calibration process to take place, this can be carried out by the dam inspection staff, without the need for intervention of information technology experts. Furthermore, because of the singular characteristics of the Cabril dam, it is expected that AR tracking will be easier and more stable at most other dams.

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.

3.1 Prototype evaluation

The prototype's performance in the real world was tested, at various 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 m from the facade of the powerplant. Furthermore, reasonably stable tracking is achievable at around 110 m from the facade of the powerplant (about 150 m from the downstream face of the dam), with a distance between the observer and the tracked Image Target of approximately 130 m (see Fig. 9). Also, at 110 m 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 per cent, 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.

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 powerplant 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.

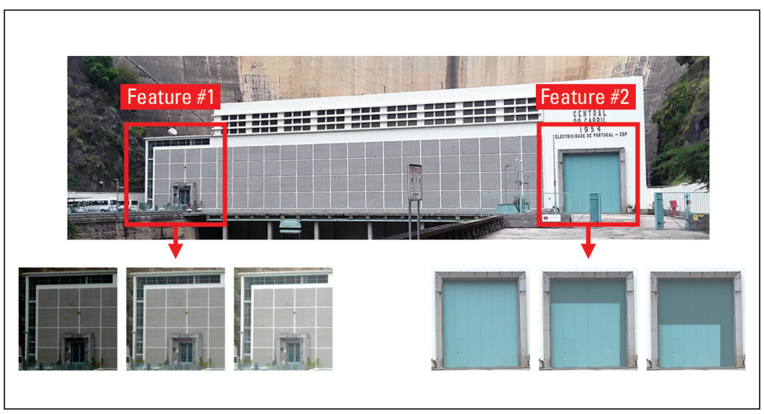


Fig. 8. The two architectural features chosen and examples of multiple image targets with different levels of luminosity and shadow coverage.

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's 'Extended Tracking', which uses the characteristics of the surrounding environment to maintain stable tracking, took over and allowed for the tracking to be maintained. However, a slight increase in the oscillation of the model was noticed.

As regards the use of multiple targets for a single digital model, the prototype successfully adopted for a specific area the Image Target of which the features were closest to the existing ones (for example, an Image Target based on a darker source image when it was dark or cloudy or a brighter one, when the sun was shining). The transition between the use of Image Targets located in different areas of the powerplant facade (for example, when the field of view included the left or right portions of the facade solely) was also almost unnoticeable, with regard to the change of the relative position of the digital model in relation to the detected target.

3.2 User evaluation

The usability of the UI and its suitability for tasks related to the safety control of dams was assessed through real-user evaluation. 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, see Photo (e), using LNEC staff directly involved in the several tasks of dam observation and structural health monitoring, namely observation technicians and structural/civil engineers, who provided first-hand feedback on the system's operation. This highly specialized personnel offered sound and knowledge-based 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.

For the assessment of the prototype's 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 would perform on a regular basis. 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 and convenience 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 short completion times (less than 30 seconds). Also, the number of wrong/failed operations was very low in both tasks, with 70 to 80 per cent of users performing the tasks with no errors.

The subjective metrics were collected through a questionnaire, where users rated the various aspects of their experience. The questions used a Likert scale between 1 (least favourable) and 5 (most favourable). The vast majority of the users considered the prototype to have a friendly UI (70 per cent rated 5 and 30 per cent rated 4), that the sensors are easy to select (60 per cent rated 5 and 40 per cent rated 4), have a suitable size (65 per cent rated 5 and 30 per cent rated 4) and, appropriate icons and colours have been used (80 per cent rated 5 and 20 per cent rated 4).

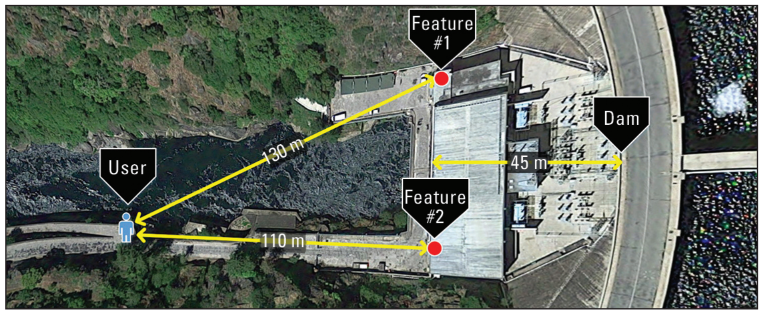


Fig. 9. Fairly stable tracking is achievable when the user is at about 110 m from the facade of the powerplant (which is situated at around 45 m from the downstream face of the dam), with a distance between the observer and the tracked Image Target (feature #1), of approximately 130 m.

3.3 Discussion

The tests have shown that at a distance of 150 m or less from the Cabril dam, the tracking is reasonably stable and therefore, the efficient and precise operation of the prototype can take place. Also, at that distance, the user can observe the full extent of the downstream face of the dam and thus, the distribution of the sensor network located along the surface and inside the structure.

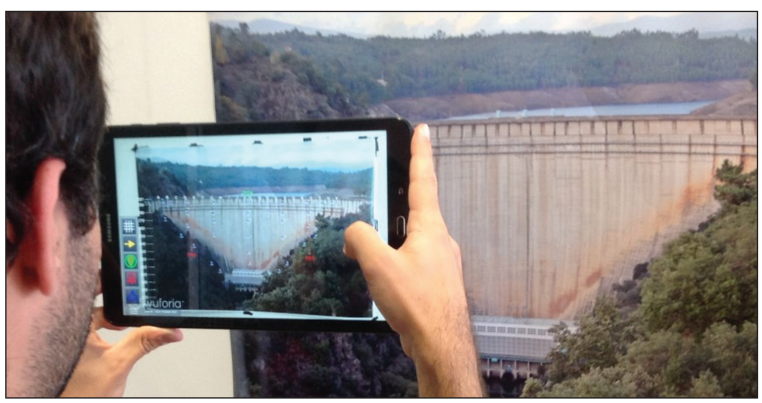
In general, the participants were very pleased with the functionality of the prototype and its UI. They found the system to be very useful and were excited about the opportunities that such a tool could bring to the improvement of their work processes. After a brief initial explanation preceding the tests, they also understood and took advantage of the possibilities offered by AR.

4. Conclusions

This work was carried out with the aim of investigating if AR technologies could be effectively used for dam safety control, namely by offering visualization possibilities that are not accessible with traditional means.

The authors observed that the inspectors could use the DamAR application in their regular activities of observing and inspecting of dams. It also supports the fieldwork of structural engineers by allowing on-site visualization of the network of sensors.

Although the prototype runs on a tablet, DamAR was developed to be easily adaptable to AR HMDs. It works by superimposing, in an AR environment, the digital model of the network of sensors to the actual



(e) User testing the prototype.

structure. By selecting a sensor, the inspector can then obtain detailed information regarding the evolution of horizontal displacements measured in that sensor over time. This information is presented in conjunction with the evolution of other relevant quantities related to the main structural features of the dam.

By allowing the display of information in-situ, directly superimposed on 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.

This work is just a first step in the process of developing a fully fledged AR application that can assist structural engineers and observation technicians with dam safety control-related tasks. The evaluation results show that AR technologies can indeed be used in dam safety control and, furthermore, that these technologies have the potential to play a central role in the future of dam safety.

The rapid progress in AR SDK's, tracking methods, the definition and overall quality of cameras and sensors, as well as the speed and efficiency of graphical processors, will undoubtedly offer more advantages for the development of DamAR, which in turn will provide more tangible benefits for the user. ◊

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