Chapter 30

The future of structural health monitoring with extended reality

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This is the author's submitted manuscript of a book chapter published in Digital Transformation in the Construction Industry, Woodhead Publishing Series in Civil and Structural Engineering. Elsevier, 2025. The final version is available at https://doi.org/10.1016/B978-0-443-29861-5.00030-5.

N. Verdelho Trindade, A. Ferreira, D. Gonçalves, and S. Oliveira, "The future of structural health monitoring with extended reality," in Digital Transformation in the Construction Industry, Woodhead Publishing Series in Civil and Structural Engineering. Elsevier, 2025, pp. 593–620, doi: 10.1016/B978-0-443-29861-5.00030-5.

Extended Reality (XR) comprises the set of technologies directed at changing users' observable reality. These technologies include most notably, Virtual Reality and Augmented Reality, but also other lesser-known modalities like diminished reality. The ongoing global transition to digital has determined the increasing adoption of these visualization and interaction technologies in the construction industry. Examples of applications of such technologies can be found for domains extending from design and planning to construction and operation. Some of the most mature applications of XR to the construction industry can be found in the Structural Health Monitoring (SHM) field. This maturity results from the tangible advantages of performance, precision, and convenience, among others, that XR technologies have been proven to bring to this area. The use of such technologies, however, is not without important challenges, which must be taken into account when researching and developing applications. In this chapter, we analyze how the different modalities of XR are being applied in the context of the distinct areas of SHM. A specific case study of the application of these technologies to dam safety control is also described. In that scope, a set of guidelines is presented to assist researchers and domain experts in implementing such solutions. Finally, a reflection on the future of XR in SHM is carried out.

30.1 Introduction

Structural Health Monitoring (SHM) can be defined as the process with which a damage identification strategy is implemented (Worden et al., 2007). It is characterized by the analysis and behavior prediction of structures using sensing devices (Habel, 2010). SHM aims to ensure integrity and safety by promoting early detection of the evolution of deterioration (Ou & Li, 2009). As such, it supports decision-making regarding the design, operation, and management of structures (Vardanega et al., 2016). Advances in sensing technologies have brought SHM data analysis to a new level. More recent sensor systems allow smarter (Ozer & Feng, 2020), real-time data acquisition, and information visualization.

Indeed, the field of SHM has been at the forefront regarding the adoption of technological innovations as a way to enhance its core processes. The efficient visualization and abstraction of structural sensor data has been an important part of this adoption. Advanced visualization technologies such as the ones associated with Extended Reality (XR) have been gradually integrating SHM processes.

The term XR gained prominence in the mid-2010s as technologies such as Virtual Reality (VR) began to converge, offering usable immersive experiences, viable as a complement or alternative to traditional visualization. XR refers to the entire spectrum of real and virtual combined environments generated by computer technology. Milgram and Kishino conceptualized this spectrum's range using the reality–virtuality continuum construct. This construct is limited by real environments at one end of the continuum and virtual environments at the other end (Fig. 30.1). VR environments are purely digital. They allow users to put on VR headsets and become fully immersed in digital environments, which have the ability to transport them to alternative realities. Real environments are, of course, the opposite, as they are entirely physical.

What lies between these two extremes (completely real and completely virtual) is commonly referred to as Mixed Reality (MR). In MR, the real and the digital co-exist in a shared environment. While realities closer to the real environment tend to be used on-site, realities closer to the digital are more commonly used off-site. An example of MR, conceptually closer to the real environment, that has gained significant traction in recent years is Augmented Reality (AR). AR allows the augmentation of the real world by overlaying relevant virtual objects on it. Another example is the lesser-known Augmented Virtuality, where virtual environments are enhanced by the projection of real objects.

Software for enabling mixed realities can be run on a variety of computational visualization devices. Devices that use conventional 2D screens, like smartphones or tablets provide a practical way of enabling technologies such as AR (Fig. 30.2). However, they do not allow the user to be adequately immersed in realities closer to virtual. For that purpose, VR Head-mounted Displays (HMD) offer full visual immersion, allowing users to abstract themselves from the real world. Likewise, AR HMDs provide users with a practical hands-free way of augmenting reality. These specialized XR devices are often equipped with gyroscopes, accelerometers and depth cameras which allow the determination of the position and orientation of the user's head within the three-dimensional space. This process is commonly known as "tracking". Real-time tracking enables the XR system to match the user's movements in the real world, to a relative orientation and position in the virtual or mixed reality counterpart experience. More recent MR HMDs (Fig. 30.3) can be used in both AR and VR experiences, even allowing the user to seamless transition between the two realities.

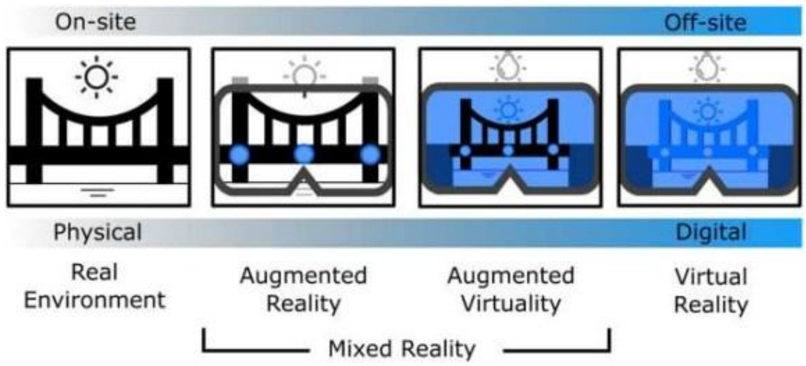

FIGURE 30.1 A simplified representation of the reality–virtuality continuum construct, which scopes the spectrum of real and virtual combined environments generated by computer technology. The continuum is limited by physical/real environments (left) and fully digital virtual environments (right). In between other realities combine physical (in black and white) and digital (in blue) in distinct proportions, and as such can be classified as mixed realities. While realities closer to the real environment tend to be used on-site, realities close to virtual reality are more commonly used off-site.

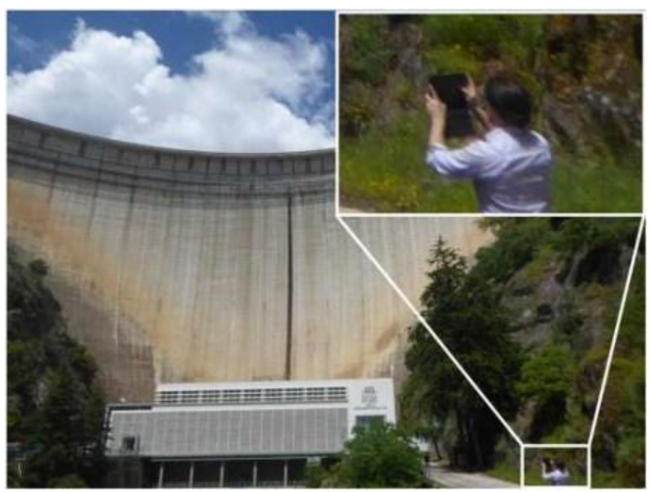

FIGURE 30.2 On-site augmented reality-enabled structural health monitoring sensor network visualization with a tablet.

FIGURE 30.3 Off-site virtual reality-enabled structural health monitoring data analysis using a wireless mixed reality head-mounted display.

The integration of SHM with XR methods began as a novelty. Subsequently, its use progressed to supporting and bolster more established, conventional methods (Koo et al., 2009). However, the swift evolution of XR hardware, such as VR and AR headsets in the last few years has made their use more convenient and substantially more affordable (Xi et al., 2022). Advances in natural interaction techniques (Galais et al., 2019), especially the ones tailored for XR, such as mid-air interaction (Bermejo et al., 2021), have also contributed to making these immersive environments more usable. As such, XR technologies have been slowly assuming the role that was occupied by conventional visualization techniques in SHM (Awadallah & Sadhu, 2023).

In SHM, this transition is noticeable with the increased use of AR applications for on-site structural information visualization superimposed on reality (Tam et al., 2023). AR methods have known advantages in this scope over conventional methods in terms of convenience. They allow hands-free visualization on-site when coupled with adequate devices, such as rugged, wireless HMDs. They also enable the visualization of data directly superimposed over the object being analyzed (Fawad et al., 2024). The framing of data within the visual context of the structure is often referred to as Situated Visualization (Satriadi et al., 2023). Such on-site contextualization has been known to potentially improve analytical reasoning and decision-making (Skarbez et al., 2019).

The tendency for replacing conventional visualization methods with XR ones has also taken place for off-site applications, with VR. VR allows SHM practitioners to, e.g., inspect difficult-to-access structures from the comfort of their office using faithful representations of the object of inspection (Omer et al., 2021). If such representations are realistic and close enough to the original (e.g., by using computer graphics photorealism [Nakamae & Tadamura, 1995] techniques such as ray-tracing [Formella & Gill, 1995]) they can also enable effective Situated Visualization (Iglesias et al., 2021). This case is commonly designated as proxied-situated visualization because of the use of a proxied physical referent (a virtual representation of the real structure) instead of an immediate one (the real structure) (Satriadi et al., 2023). Such realistic, immersive experiences have been known to increase the sense of presence (the sense of effectively being there, on-site) (Ilker Berkman et al., 2019). An increased sense of presence has been recognized as a central factor in incrementing engagement and understandability (Skarbez et al., 2019). When coupled with real-time data sourced from real structures, these virtual representations are often designated as Digital Shadows (Liebenberg & Jarke, 2023). When the data flow is bi-directional (from the structure to its representation and vice-versa), they are called Digital Twins (Havard et al., 2019).

Immersive virtual environments have also been known to increase depth and spatial relationship perception in data analysis scenarios (Guo et al., 2022; Vienne et al., 2020). However, such an advantage has to be actionable within those environments. As such, in addition to model realism, applications should also implement mechanisms that take advantage of the spatiality of immersive environments (Schnabel & Kvan, 2003). Natural interaction techniques allow a more intuitive way of exploring the 3D space within such environments. Moreover, because they more closely mimic human interaction with real objects, they will more likely maintain the sense of presence (Kim et al., 2020). Likewise, a reliable simulation of interaction in the real world cannot be limited to audiovisual feedback. Instead, it should be a rich multisensorial experience that can also transmit e.g., the sense of touch and smell. As such, VR analytics experiences will greatly benefit from haptic, olfactory, thermal, proprioceptive, and vestibular feedback (Gibbs et al., 2022).

The deployment of XR technologies in SHM is interdisciplinary in nature. It presupposes the participation of professionals from various fields. Within this collaborative approach, successful XR functionality integration and application in SHM tasks will be more likely (Sadhu et al., 2023). In that scope, there are two main scientific areas to which elements taking part in the deployment of such applications notably belong: structural/civil engineering and computer science/engineering.

Structural engineering professionals are prime players in applying XR to SHM. Their expertise is essential across the several stages of this process (Malekloo et al., 2022). They are ideal for first identifying aspects of particular types of structures or monitoring tasks where XR can be applied to improve workflows (Awadallah & Sadhu, 2023). They can give their input on aspects such as the accuracy and relevance of the XR visualizations during the development process. They can also suggest improvements based on their practical knowledge. Furthermore, they are ideal for training other engineers and inspectors on using XR SHM applications.

Due to their on-site experience, field inspectors involved in monitoring structures are equally valuable (notably in the development of AR applications, as we will see further), as they can provide fundamental insights into the field monitoring processes (Fawad et al., 2023). Likewise, civil engineers and structure-specific engineers, such as bridge or dam engineers, are fundamental when addressing, e.g., the application of XR to the SHM of particular structure types.

In what respects the computer science area, the creation of XR applications for SHM also implies multiple facets of expertise. Computer scientists and engineers must always work closely with SHM domain experts to produce practical applications. In that scope, data analysts are fundamental in analyzing and selecting relevant SHM data types and producing actionable insights (Pohl et al., 2022). Information visualization experts make abstracted representations of that data and insights within the XR environments. For such representations to be interactive, they must accept user input (Zhao et al., 2022). Interaction mechanisms must be devised so that the user can interact with the different virtual objects inside the XR environment. That is where human-computer interaction experts play a fundamental role. They design and implement XR interfaces, which enable the necessary mechanisms to make the application features actionable to the user (Han et al., 2023).

Computer graphics experts are at the heart of creating extended reality environments. They are responsible for modeling and texturing the 3D world (Hughes, 2014), including the structure to be analyzed and the terrain surrounding it. In that process, they must select the proper graphical techniques that guarantee an appropriate realism level (including realistic lighting and shading) (Pharr et al., 2023). They must also implement accurate physics-based behavior within the XR environment (e.g., collisions, fluid simulations, or structure dynamics) (Marschner & Shirley, 2022). These factors must be balanced with the efficient rendering of the 3D scenes in real-time to ensure an appropriate responsiveness of the environment that will not interfere with the efficiency of SHM operations.

Despite all the advantages above, XR technologies, in their current state of development, have relevant limitations when applied to real-world SHM scenarios. One of these limitations consists of the XR devices' technical limits and the infrastructure (e.g., networking) they use to provide an integrated experience. An example of such a limitation is the visual clarity (Wang et al., 2024) provided by commercial HMDs. While the field of view and resolution per eye (Wang et al., 2022) have been increasing consistently in the last few years, the number of pixels packed in each degree of the field of view (Zhan et al., 2020) still can't provide a completely seamless experience (Sauer et al., 2022). Such experience should ideally and ultimately allow a natural visualization, where virtual elements are indistinguishable from real-world elements.

One other important technical limit is the battery duration, which is all the more relevant for on-site XR applications. Indeed, while battery technology is evolving rapidly in different industry fields, most HMD's battery runtime is still restricted to 2-3 hours of heavy use (Duinkharjav et al., 2022). This aspect is not as evident in mobile 2D screen devices, which provide a less immersive but more durable AR experience (Ali et al., 2023).

A second set of limitations concerns how the environment affects the performance of the XR experience. An example of such a limitation is the robustness of HMDs for on-site augmented SHM (Colombo et al., 2019). Environments with extreme temperatures, humidity (Xu et al., 2023), or dust can influence the device's sensor reliability and other aspects of the hardware performance (Bottani et al., 2021). However, some manufacturers are already focusing on producing special editions of consumer XR HDMs which have been ruggedized for activities such as engineering, and construction on-site use.[1]

Likewise, many SHM applications require high bandwidth (for example, fetching BIM data remotely), often not directly available in remote or underground locations. However, this is a transversal problem for all devices and applications that rely on remote SHM data, not only the XR ones. Furthermore, technologies such as global satellite internet services[2] can be a way of hindering this problem, at least in some respects.

A third set of limitations concerns how humans react differently to XR experiences. An example is motion sickness (also known as cybersickness), typically associated with VR use (and AR to a lesser extent), which consists of user nausea and disorientation (Chang et al., 2020). Motion sickness results from sensory discrepancies between what the users naturally perceive and what they experience in the VR environment (Golding, 2016). Such discrepancies can result, among other factors, from the latency between the user's movement and the corresponding change in the virtual environment (directly related to low refresh and

[1] Such as Microsoft's "HoloLens 2 Industrial Edition" and "Trimble XR10 with HoloLens 2": https://www.microsoft.com/en-us/hololens/buy
[2] Such as the ones provided by Starlink: https://www.starlink.com/

frame rate – a technical limit) (Saredakis et al., 2020). However, this limitation is transversal to all XR use, not only to SHM applications.

In this chapter, we preview how the democratization of XR will impact the future of SHM. We start by analyzing existing research work related to XR applications to SHM (Section 30.2). We then present a case study of an application of XR to a specific area of SHM, the dam safety control (Section 30.3). Based on this case study and the analyzed existing research work, we establish a set of guidelines aimed at supporting the research and implementation of XR applications in SHM in its several stages (Section 30.4). Finally, we offer a reflection on how the future of SHM will possibly be with XR technologies (Section 30.5), before moving to the final conclusions (Section 30.6).

30.2 Current State of XR in SHM

The use of XR technology in Architecture, Engineering and Construction (AEC) applications has increased significantly in the last decade (Verdelho Trindade et al., 2023). This tendency has also been specifically observed in the SHM field (Xu & Moreu, 2021). In this field, existing research on XR applications extends to damage identification, structural data management, analysis, and modeling. XR has also been addressed in SHM tasks focusing on specific structures, such as bridges, tunnels, buildings, or dams. Secondary studies[3] (Kitchenham, 2004) have additionally been carried out addressing the application of XR to SHM, like the works by Catbas and Avci (2023), Malekloo et al. (2022), Palma et al. (2023), and Xu and Moreu (2021).

This section addresses relevant examples of existing research on applying XR to SHM in different areas. A set of 44 primary studies obtained through a structured search in the Scopus electronic library[4] were analyzed. These studies were framed in three categories, corresponding to the most common application areas of XR in SHM: damage detection and localization, data management and analysis, and structural modeling and simulation. A brief bibliometric analysis was carried out, where relevant tendencies of the analyzed studies were compared and highlighted.

30.2.1 Damage detection and localization

Damage detection is a fundamental process in SHM, consisting of identifying and localizing the presence of damage in a structure (Fuentes et al., 2022). This process is supported by various methods, such as visual inspection, sensor-based monitoring, and nondestructive testing (Haider et al., 2022). Kamat and El-Tawil addressed the use of AR for structural damage detection in buildings (Kamat & El-Tawil, 2007). They superimposed Computer-aided Design (CAD) representations of structural walls to live video feed of the real walls to measure displacements. Their work was directed towards detecting and assessing earthquake-induced wall drifts in buildings. Shin and Dunston (2009) used AR for steel column inspection. Their system allowed the detection of defects in construction by superimposing the virtual 3D model of a column

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[3] The term 'secondary studies' is used in this work to designate studies consisting of the systematization of data previously gathered from a set of selected relevant primary studies.
[4] The following search string was used for that purpose: TITLE-ABS ("virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "diminished reality") AND TITLE-ABS ("structural health monitoring" OR "shm").

to a video feed of the real column. They compared the AR system with conventional inspections to detect deviations in the position of anchor bolts and column plumbness. They concluded that while AR is less precise for such tasks, it is simpler and faster and provides results within standard tolerances.

Teixeira et al. (2014) proposed using AR HMDs to control Unmanned Aerial Vehicles (UAV) in the structural inspection of buildings. In the suggested solution, the movement of the UAV is controlled through the operator's head position and gestures. Salamak and Januszka (2015) addressed using AR to inspect concrete bridges. They proposed using HMDs to show users relevant information such as sensor measurements, distances between elements, or existing cracks dimensions superimposed to reality. Their on-site system can also be used to record the inspector's annotations, including photos and voice recordings.

The precision of AR in taking measurements in the context of structural inspection was assessed by Moreau et al. (2017). They used HMDs together with the HoloMeasure application. A result of less than 2% error was obtained when taking measurements from up to six meters distance, in and out of the line of sight. The feasibility of using AR for inspecting segment displacement during tunnel construction was carried out by Zhou et al. (2017). The misalignment between segments was detected by superimposing a CAD virtual baseline model to a video feed of the actual tunnel. The results indicate time savings compared to traditional inspection methods. The visual inspection of bridges through VR was also addressed by Omer et al. (2018). They argued that the off-site analysis of realistic 3D models of bridges with up-to-date textures using VR environments can offer inspectors a more convenient way of assessing the structural condition. The integration of AR for on-site visualization of nondestructive testing results superimposed to concrete structural elements was addressed by Schickert et al. (2018). They developed a solution that allows the user to have a kind of viewing window into the interior of concrete elements. It allows the user to localize the steel reinforcement 3D representation based on ultrasound and radar data. Such a solution can aid in on-site inspection, facilitating the assessment of results and simplifying interpretation.

An MR framework for aiding on-site infrastructure inspections was proposed by Karaaslan et al. (2019). The framework allows the detection of structural damage in real-time using artificial intelligence techniques. It highlights the location of the damage and presents it to the inspector wearing an MR HMD by superimposing that information into reality. The application of such systems enhances the capability of inspectors to locate damage in real time without the need for manual measurements. The research by Yamaguchi et al. (2019) focused, among other aspects, on projecting detected cracks onto concrete structures using MR. They developed a prototype that allows inspectors to confirm crack dimension and localization by superimposing previously acquired data with the actual structure. Athanasiou and Salamone (2020) focused on visualizing steel reinforcement of concrete elements. They developed an AR prototype that allows the inspectors to have an X-ray view of those internal components. That capability enables, for example, the determination of the number of steel stirrups that cross a crack. Such knowledge allows the inspector to make an educated decision concerning the condition of the analyzed structural element.

Kilic and Caner (2021) used AR to visualize data resulting from ground penetrating radar, laser distance sensors, and infrared thermography superimposed to bridge structures. The system was directed at aiding inspectors in the detection and localization of cracks and rebar corrosion. Aguero et al. (2021) addressed how AR could be used on-site to aid inspectors in SHM tasks. In particular, they focused on the capabilities of AR to measure cracks and document their geometry. Their prototype allows inspectors to pin specific points in the structure to define virtual markers on the surface of a crack. This set of virtually located points allows the system to measure and register the cracks' geometry. Moreu and Malek (2021) also delved into the detection and measurement of cracks in bridges using AR. They focused on evaluating the precision of AR crack measurements, namely its length and thickness. Tadeja et al. (2021) addressed interaction within VR environments for taking engineering measurements in photogrammetric 3D models. In that scope, they explored the efficiency of using bimanual gestural input and gaze tracking within the VR environment. Wang et al. (2021) used AR coupled with deep learning techniques to enable automated damage detection in real-time. They presented a set of algorithms for detecting and classifying corrosion phenomena in structures. The data is acquired and processed, and the resulting information is superimposed on the structure using AR HMDs.

The on-site collaboration between humans and inspection robots was explored by Al-Sabbag et al. (2022). They proposed a system where a robot, controlled by an inspector, performs 3D image acquisition of the structure, and processing, including damage detection and segmentation. The processed data is then transmitted to the inspectors' MR HMD to visualize damage information superimposed on the real structure. John Samuel et al. (2022) addressed using AR in bridge inspection for on-site damage annotation and accessing historical defect information. Their system uses a mobile touch device to allow inspectors to overlay relevant content to the actual structure. Mohammadkhorasani et al. (2023) used AR and computer vision techniques for automatically detecting and localizing fatigue cracks. Their work focuses on representing the results of a video processing algorithm for crack detection overlapped on the structure being inspected. The procedure provides fatigue crack detection results in near-real-time for on-site structural inspectors. Montes et al. (2023) used deep learning and AR methods for damage detection in the scope of a bridge visual inspection system. The system can detect and localize corrosion damage, which can be highlighted and superimposed on the bridge using AR.

30.2.2 Data management and analysis

SHM processes can generate large amounts of data resulting from monitoring systems. This data has to be carefully managed so it can be efficiently accessed and analyzed. Structural information should also be properly abstracted and framed in the scope of the monitored structure (Valinejadshoubi et al., 2019). These procedures allow the structural data to be actionable, enabling easy extraction of meaningful information to support decisions.

As early as the late 1990s, Stalker and Smith (1998) took the first steps in applying AR to support remote monitoring of structures. With that objective, they overlapped CAD images containing the positions of sensors for measuring local deformations, to live video of a bridge. The ability to document a bridge's physical condition using VR was also addressed by Jáuregui and White (2003). They implemented an interactive environment using photos of a bridge and included relevant structural information using selectable hot spots. The researchers argued that using VR and different media types could result in a significantly higher level of detail when compared with written bridge inspection reports. Park et al. (2013) used AR to visualize the location of embedded sensors in structural concrete components. The prototype developed by these researchers allows the superimposition of concrete curing strength monitoring data to structural elements on-site. AR was set up with a touch-screen mobile device.

The use of spherical imaging VR in bridge SHM data visualization was addressed by Napolitano et al. (2017). They used interactive spherical panorama images of a pedestrian footbridge instrumented with fiber-optic strain gauges. Users can select certain points of interest in the panoramas to highlight specific types of damage. The virtual environment includes additional 2D images that detail the structural damage. A management system for SHM data in the construction phase of large-scale structures was developed by Ni et al. (2017). The system uses VR to allow the visualization of spatiotemporal data by associating the graphical model with construction scheduling. Peres et al. (2018) mapped the communicational, motor, perceptual, and mediational components involved in monitoring cracks in dams using a taxonomy of tasks. The proposed taxonomy aims to provide a more informed and structured way of applying AR to dam safety control.

Napolitano et al. (2019) applied AR in on-site SHM annotation. They developed a system that allows an inspector, using a mobile device like a tablet, to highlight relevant information directly over the real structure. The annotations can also be reviewed off-site using a desktop application. Dam et al. (2020) research looked into extending human capabilities in accessing hard-to-reach areas. They addressed how AR could be used to guide drones in infrastructure inspection tasks. The results show that the application of AR in drone guidance can be helpful in certain inspection tasks. A framework that aims to integrate AR and Building Information Modeling (BIM) to facilitate bridge SHM was proposed by Dang et al. (2020). They suggest using AR devices to feed new information and verify existing structural data in the BIM model. A collaborative annotation AR system for the inspection of prefabricated buildings was implemented by García-Pereira et al. (2020). The tool allows multiple inspectors to take concurrent geolocated annotations, including different media types. A mixed-reality application for aiding bridge structural inspectors was developed by Nguyen et al. (2020). The off-site application allows users to visualize defects in a virtual model of the bridge augmented in an office space. The representation of the bridge includes crack information, namely length, orientation, and cause.

Maharjan et al. (2021) analyzed the integration of low-cost structural sensors and QR code scanners with AR for infrastructure inspection. Their proposed system allows users to visualize real-time structural data superimposed on the structure being inspected. They argue that such a system may help inspectors contextualize data on-site and support decision-making. Savini et al. (2022) developed a VR system to manage and visualize historical bridge structural information. The system allows users to explore the location of bridges at a territorial level and select a specific bridge to visualize. The visualization is made in a photorealistic environment and includes accelerometric data and degradation information. Tam et al. (2023) focused on implementing effective visualizations for structural monitoring tasks to support decision-making better. In that scope, they developed an AR application that can superimpose historical sensor data and damage information to real-world structures. Such representations allow SHM professionals to better scope the data in the context of the structure that is being analyzed.

30.2.3 Structural modeling and simulation

Data acquired from monitoring systems can be used to update and improve models that reproduce the analyzed structures' geometry and behavior. The fidelity of these models is crucial for processes such as accurately simulating and predicting the behavior of structures (Fawad et al., 2023). Its precision and realism are also decisive for providing off-site mechanisms for remote inspection of structures (Einizinab et al., 2023).

In the structural modeling and simulation scope, Qiu and Gao (2010) addressed the use of VR for bridge deformation visualization. They built an accurate VR model that simulates the behavior of a bridge over time. Laser scanning was combined with hydrostatic leveling to determine the structure settlements. The work by Attard et al. (2018) focused on visualizing tunnel structures using VR. They used a remotely operated robot with cameras to capture images of the tunnel's interior. The images were then used to reconstruct the 3D tunnel model. This model was integrated into a VR environment to allow users to visualize the surface condition of the tunnel. The representation of SHM experiences in historical constructions using VR was the focus of Burgos et al. (2019)'s work. They built a virtual building model where real-time SHM data was used to simulate its structural state. Among other applications, this solution can be used for research and educational activities. Bacco et al. (2020) focused on the simulation of the structural behavior of ancient buildings using VR. They built a prototype that allows users to explore the virtual reconstruction of a monitored structure. Within the VR environment, the users have direct access to the data measured by the real structural sensors.

A panoramic spherical image VR model with real-time SHM data of a tunnel was developed by Ma et al. (2020). The model allows users to roam tunnels and visualize information from structural sensors and historical inspection data. Luleci et al. presented a VR prototype capable of accurately simulating the dynamic response of a bridge. The prototype allows multi-user interaction in a collaborative environment designed for decision-making. The process of planning permanent geodetic monitoring installations for SHM was simulated in VR by Bauer and Lienhart (2023). They developed an accurate virtual environment capable of simulating geodetic total stations. The simulation aims to facilitate the detection of problems like obstructed lines of sight or automatic aiming issues. Peng et al. (2023) created a VR simulation framework for developing and testing autonomous UAV structural inspection procedures. The simulation includes features such as algorithmic virtual sensing and control of the UAV. Such systems allow the optimization of structural inspection procedures in complex or difficult-to-access environments.

30.2.4 Trends overview

In order to obtain an overall assessment of relevant relations between SHM and XR technologies in the analyzed studies, an author's keyword density and relationship analysis was first carried out (Fig. 30.4). This analysis shows a prevalence of studies where AR/MR was applied in crack detection. These studies also have an intimate connection with BIM and the use of UAVs. Studies that applied VR to SHM did it mainly in the scope of information visualization in immersive environments. They used BIM data and 3D models built from point clouds collected with laser scanning. There is a significant prevalence of VR in studies concerning SHM in historical buildings. We can also see that AR was the most mentioned XR technology keyword, followed by VR and MR. This tendency is likely indicative of a strong on-site component in the research of the application of XR in SHM.

The characteristics of the studies were also assessed through a more in-depth analysis of its full texts. This assessment supported the XR technologies ratio addressed in the primary studies obtained in the keyword analysis. Indeed, it confirmed that most studies were focused on AR (55.8% of the studies), followed by VR (34.9%). MR was addressed in 9.3% of the studies. Regarding the distribution by SHM category (according to the classification adopted in this section), 47.6% of the studies focused on applying XR to damage detection and localization, 35.7% to data management and analysis, and 16.7% to structural modeling and simulation.

Concerning the characteristics of the XR technological application, studies were framed by the type of display and input used. Regarding the type of display, 59.5% of the studies used HMDs, and 40.5% used 2D screens (desktop monitors, smartphones, and tablets). With respect to the type of input (Fig. 30.5), most (31.1%) of the studies used body tracking (mainly through depth cameras on the XR devices) as input modality. These were followed (26.7%) by the use of tracked objects (e.g., AR and VR controllers). Touch screens (20.0%) and more traditional forms of input, like keyboards and mice (20.0%), are still discussed in a significant part of the studies analyzed. Voice input is used in 2.2% of the studies, especially in conjunction with other forms of input, like body tracking (mainly through AR HMDs, like the Microsoft HoloLens, which incorporates speech recognition capabilities).

Bridges were the type of structure/physical environment addressed the most (40.9% of the studies) in the analyzed studies (Fig. 30.6). Buildings (29.5%) and tunnels (6.8%) followed them. Dams (2.3%) and urban landscapes (2.3%) were the least discussed. We can see that a significant portion (29.5%) of the studies do not address a specific type of structure but are instead dedicated to a particular SHM task with a generic structure application.

Finally, concerning their country of origin (nationality of first author), most studies (40.5%) were developed in the USA, followed by China (9.5%), South Korea (7.1%), and the United Kingdom (7.1%). The remaining 35.7% of the studies originate from other countries.

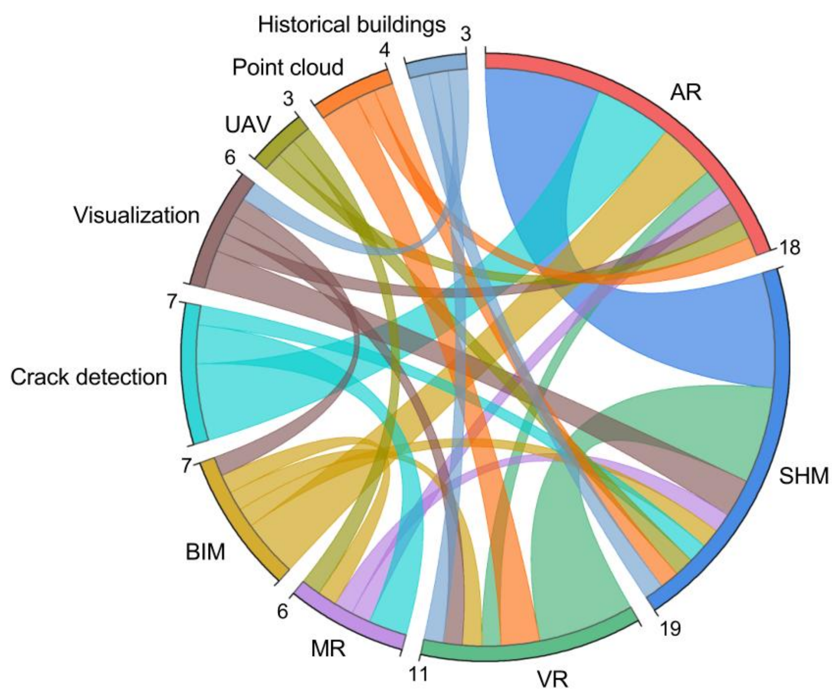

FIGURE 30.4 Relations between the top 10 most used author's keywords in the analyzed studies. Keywords with the same meaning (e.g., 'VR' and 'virtual reality') were merged.

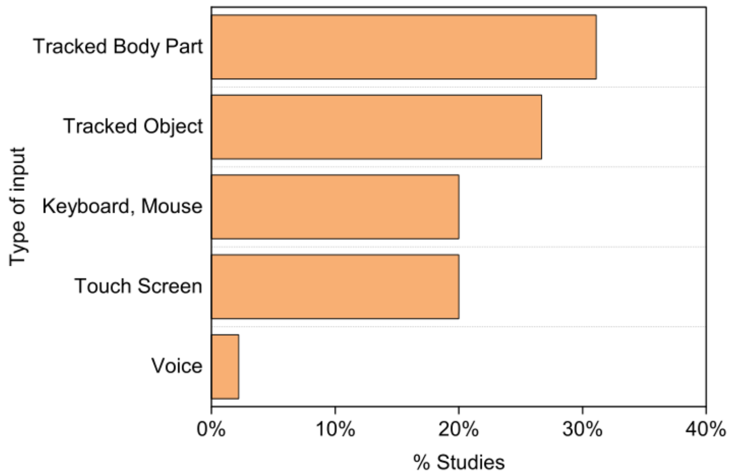

FIGURE 30.5 Number of studies addressing a specific type of input.

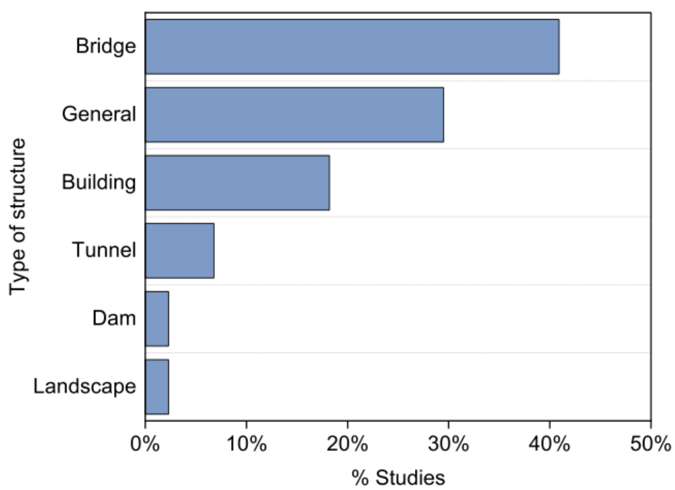

FIGURE 30.6 Number of studies addressing a specific type of structure/physical environment (the 'General' category concerns studies that are not focused on a single, specific type of structure).

30.3 Dam Safety Control: An XR in SHM Case Study

This section describes a case study of applying XR technologies to dam safety control. Dam safety control is an SHM activity that involves analyzing, monitoring, and behavior prediction of different aspects of dams (Li et al., 2020). It comprehends several on-site activities commonly carried out in the scope of visual inspection campaigns. These include structural pathology detection and localization. Dam safety control is equally comprised of off-site activities, such as behavior prediction using theoretical prediction models and its comparison with the measured behavior (Carvalho et al., 2023). The structural data that serves as a basis for these activities originates from the vast sensor networks installed inside the dam structures and surrounding areas (Oliveira et al., 2022). These sensors produce massive datasets that can only be made actionable using adequate visualization techniques that provide proper data abstraction and contextualization. It is within this context that the case study described below was developed.

30.3.1 Problem description

Laboratório Nacional de Engenharia Civil (LNEC) is a Research and Development (R&D) institution that, among other missions, assists the Portuguese Government by providing technical support related to the safety control of dams. This mission is carried out by the Concrete Dams Department (CDD) at LNEC. At CDD, sensor-originated structural data visualization has been carried out using conventional technological means (2D screens and keyboard/mouse). These means have been used for many years and, as such, are deeply embedded in the workflows of their staff. In that scope, specialized desktop software has been used, some of which were entirely or partially in-house developed. Notable examples are the information management system GestBarragens (Castro et al., 2012), which includes visualization modules for historical data and physical and mathematical behavior models. Another relevant example is DamDySSA4.0 (Oliveira et al., 2022), a Finite Element Method (FEM) desktop software for dynamic analysis and visualization of concrete dam structural data. For on-site operations, CDD has relied, in the last decades, on handheld PCs (personal digital assistants/PDA) for manual registration of sensor data. It also has had no specialized tools for on-site structural sensor data visualization.

CDD had been considering using XR technologies to expand and supplement its existing visualization means as early as 2012 (Gamito et al., 2012). Such desire came from the limitations that the exclusive use of conventional means presented. Indeed, the visualization of structural data is traditionally carried out with limited or no visual reference to the area of the dam being analyzed. In the most optimistic scenario, traditional visualization techniques allow engineers to analyze structural information superimposed on a 3D representation of the dam on a 2D screen. However, in most cases, data is analyzed in 2D/3D charts without visual contextualization with the dam's physical structure. Such restraints lead to limited understandability in a domain where the data so closely relates to the physical object being analyzed and where, as such, spatial relations, contextualization, and awareness are key. XR environments can promote improved depth and spatial relationship perception (Guo et al., 2022; Vienne et al., 2020), which are essential for obtaining insights e.g., from the displacements, stresses, and strains along dam structures. Analysis within immersive environments has been known to support engagement, decision-making, and improve contextual understanding of the data compared to conventional analysis (Marriott et al., 2018; Nouri et al., 2022; Skarbez et al., 2019).

The dam safety control activity developed by CDD encompasses other players besides dam engineers and inspection technicians. Dam managing entities, state authorities, and the general public are also relevant elements of dam safety control and hydropower projects in general. XR can be used to stimulate awareness of the role of dam safety control in the safety of populations and the management of water resources. By showing inherent processes of dam safety dynamics that otherwise could not be seen in real life, XR immersive environments can promote the participation of populations in that activity.

30.3.2 Conception

It was in the scope of a cooperation initiative between Lisbon and LNEC that a set of XR tools aimed at enhancing dam safety control data visualization were set to be developed. These tools were aimed at both on-site and off-site visualization through the use of AR and VR technologies, respectively. They were directed at abstracting and contextualizing the data with dam structures.

Two use cases were circumscribed with the CDD for dam safety control XR visualization. The first was instrumentation observation. This activity involves observing sensor networks to assess their condition and analyze recorded values over time to detect anomalies. The second use case was the visual inspection of the structure, which consists of technical visits to monitor detected anomalies or find new occurrences. This activity implies documenting aspects like the type of degradation/pathology, its dimensions, or severity level.

Instrumentation observation was identified as the use case that would potentially benefit the most from XR visualization. An on-site tool (T1) was proposed that would allow engineers and observation technicians to look at a dam with an XR device and visualize the location of sensors in its interior. With such a tool, they could easily find a specific sensor's location without consulting the structure blueprints. This tool should also allow users to check the evolution of values registered in sensors over time for on-site detection of anomalies and sensor malfunction. A subset of sensor types was selected for a proof-of-concept prototype. As such, the visualization was limited to sensors used to register structural displacements (such as plumblines and Global Navigation Satellite System (GNSS) equipment).

AR was selected as the obvious XR technology for T1, as it would allow the superimposition of sensor information over the real dam. Because of the typically harsh conditions in the dam surroundings, mobile devices (smartphones and tablets) were selected as the most appropriate devices targeted by the tool. While AR HMDs offered hands-free operation and the possibility of natural interaction, they lacked roughness and battery life for practical on-site operation. The characteristics of the most recent HMDs hinder some of these limitations. However, they were still very relevant at the time of the tool's conception.

Two complementary tools (T2, T3) were proposed for off-site XR visualization. The first (T2) should allow users to visualize the location of the sensor networks in the context of a 3D representation of the dam. It should also enable the observation of the evolution over time of the registered values using standard 2D charts/idioms. The second (T3) should support the visualization of spatial idioms depicting displacements obtained using theoretical structural prediction models directly over a representation of the dam for a contextualized analysis. In addition, T3 should allow the visual comparison between these displacements and sensor-measured displacement values. VR was selected as the adequate XR technology because both T2 and T3 would be used in an office environment. HMD was chosen as the appropriate target device due to its immersive capacities.

The feasibility and effectiveness of the off-site and on-site tools need to be assessed using a real-life dam. For that purpose, the CDD suggested the Cabril Dam, a large double-curvature concrete arch dam located in the Zêzere River, in Portugal (Oliveira and Silvestre, 2017). The Cabril Dam was selected for being an infrastructure whose behavior has been widely studied. It was also a challenging worst-case scenario example for applying XR technologies. These challenges result from its large dimensions (132 m tall and 290 m wide) and concrete faces with homogeneous texture, which would negatively impact AR tracking.

30.3.3 Implementation

The first step in the development process was choosing a graphical engine that could handle the representation of the data idioms, sensors, and dam models. The Unity graphical engine was chosen for the development of the three tools. This engine offers rapid application development (using the C# programming language) paired with broad compatibility with most XR devices, operating systems, and frameworks.

For the development of T1, Unity was coupled with the Vuforia software development kit. Vuforia handles AR tracking using computer vision technology. The chosen tracking technique within Vuforia works by pairing previously captured seed photographs (named "image targets") of notable points of the dam with the video frames acquired by the mobile device camera. This process is carried out in real-time and allows the superimposition of the virtual 3D elements to reality on the tablet or smartphone screen.

T1 was meant to superimpose the displacement sensor networks to dam structures, allowing users to interact and visualize sensor historical data. To ensure the versatility of T1 in its applicability to different dams, the configuration of sensor network characteristics had to be flexible. As such, the sensor network's augmented representation was modeled by defining each sensor's type and spatial position. Sensor network layout data can be imported from configuration files or directly read from a dedicated database. The registered sensor values are also obtained similarly. They are automatically associated with a specific sensor for representation in 2D line charts.

For our case study, the Cabril Dam, we opted for contemplating symbolic representations of plumblines, GNSS devices, and geodetic marks. The sensor network model was then accurately positioned within the AR environment by pairing notable points' virtual location with its location in the real world. When using the application, the users can point the device to the dam and visualize the several sensor networks superimposed on the actual structure (Fig. 30.7). The sensor types are distributed by different layers, whose visibility can be toggled on or off using a menu on the left of the screen (Fig. 30.8). By touching a specific sensor, they can bring up 2D line charts with the historical evolution of displacements measured in that sensor.

T2 aimed to reproduce some of the features of T1 but using immersive environments and a digital representation of the dam instead of the real dam. Its development started with the implementation of the interface. This interface included mechanisms for navigating the environment, making the sensor networks visible or invisible, and visualizing idioms of the measured values. These idioms were represented over virtual panels that can be positioned freely in the immersive environment (Fig. 30.9). Users can navigate inside the dam structure, observe the sensor networks, and select specific sensors to obtain further information (Fig. 30.10). The procedure for populating the virtual environment with sensor representations based on the data obtained via a connection to an SHM database was also implemented. This base framework was then applied to the Cabril Dam case study. Adequate models of the dam structure, water bodies, and surrounding terrain had also to be built. The realism of such models was key for a faithful situated immersive experience.

FIGURE 30.7 General view of T1 interface (mockup) shows the menu system on the left and a window panel for zooming in on selected areas of dams on the right.

FIGURE 30.8 A screenshot of T1 being used on-site with the sensor network's selected layer (geodetic marks) superimposed on the dam.

The model's construction started with a point cloud of the dam and nearby terrain obtained through 3D laser scanning field campaigns conducted by LNEC. The next step consisted of additional processing to eliminate noise, outliers, and artifacts (Wolff et al., 2016). For surface reconstruction (Lim & Haron, 2014), surface-based methods (Berger et al., 2017) were used. The resulting mesh was then refined through smoothing, decimation, and hole filling (Botsch et al., 2008). For texturing (Worley, 2003), a photo mosaic was assembled using images captured on-site during the field campaigns with the multi-sensor laser scanner. This texture was then applied to the mesh using texture mapping (Heckbert, 1986). For the terrain, a similar procedure was carried out. However, in addition to texturing with a photo mosaic, the terrain was also populated with models of trees, rocks, and bushes for increased realism (Fig. 30.11).

Unlike T2, which focused on representing sensor networks, the third tool, T3, was characterized by directly enabling the spatial representation of sensor-measured values over dam structures (instead of its 2D representation using panels) and introducing more advanced analytics features (Sequeira, 2023). CDD circumscribed the visualization of the displacements of dams directly represented over the virtual structure as one of the main requirements of this prototype. The other main requirement was the visualization of the structural modes of vibration for multiple frequencies. Likewise, the users should be able to section the displacements' representation in distinct ways for a more in-depth analysis capability.

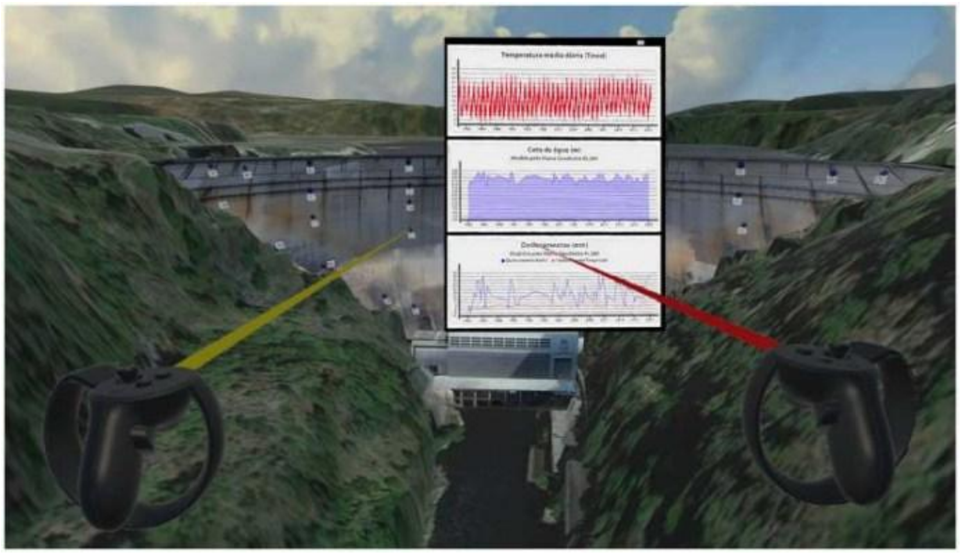

FIGURE 30.9 A view of T2 interface (mockup) shows the structural data idiom visualization panels in the foreground and the dam structure model in the background.

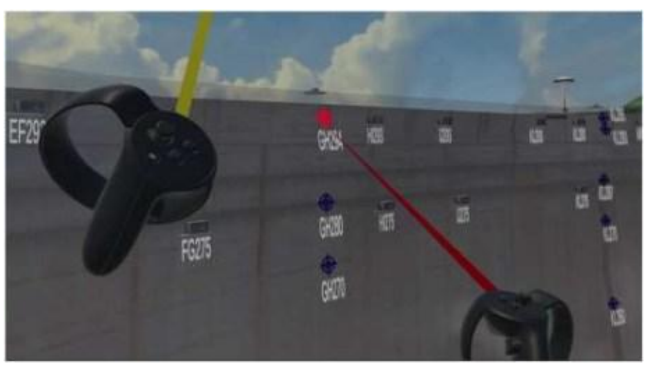

FIGURE 30.10 Users can navigate inside the dam structure, observe the sensor networks, and select specific sensors to obtain further information.

Due to the dynamic nature of the idioms represented directly over the structure model, they had to be implemented programmatically using the graphical engine. These idioms consisted of spatial heatmaps whose distance from the structure and color variation depended on the magnitude of the displacements.

Using the same variable for both channels (position and color) is a common practice in dam engineering to improve the visibility of the most structurally solicited areas of the dam (Oliveira et al., 2022). Similarly to T1 and T2, T3 is connected with an SHM database to directly import the measured sensor values. These values were then used for the representation of the spatial idioms.

T3 allows users to visualize the theoretically predicted displacements on top of dam representations. They can manually change the upstream water level and observe its repercussions on displacements (Fig. 30.12). Similarly, they can change the scale factor of the displacements to make the differences between the influence of different water levels more visible (and consequently more actionable). The users can also select the visualization of the structure's vibration modes, which will be animated in the virtual environment.

FIGURE 30.11 The T2 immersive environment includes models of the dam structure, surrounding terrain, water bodies, and sensor networks.

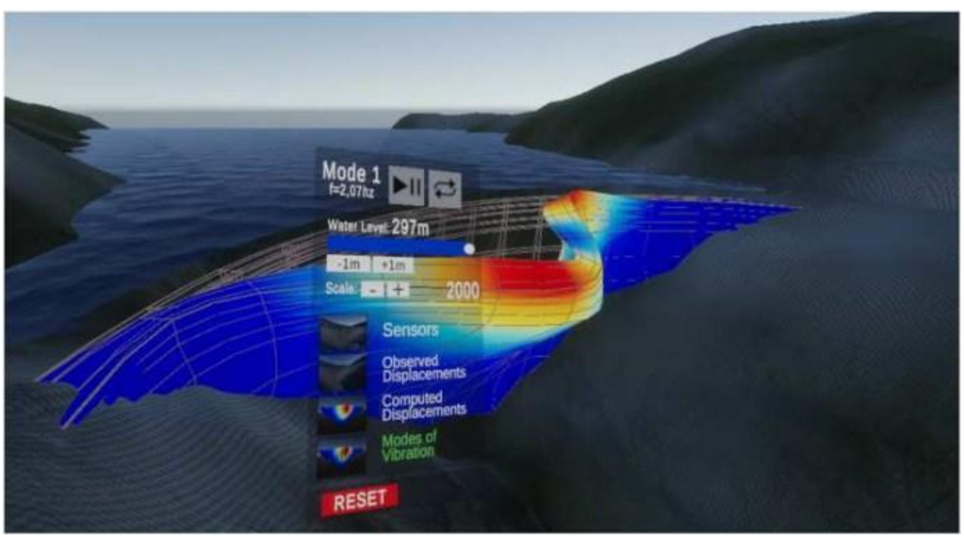

FIGURE 30.12 T3 immersive environment enables spatial representations of the theoretically predicted displacements directly over the Cabril Dam structure model. Users can also visualize animations of the structure's vibration modes.

The T3 tool enables the joint representation of the measured displacement vectors and the spatial heatmap of the theoretical displacements (Fig. 30.13). This representation allows a straightforward comparison of dams' predicted and observed behavior. Furthermore, T3 offers advanced analytics functionalities that allow for the segmentation of both the structures of dams and the idioms. This segmentation can be carried out by individually representing, for example, a specific portion of the structure, allowing users to see a desired section of the dam. The structural entities of the dams can also be isolated, as in Fig. 30.13, where only the displaced construction joints in the structure are shown.

T3 also introduces two graphical fidelity modes between which users can switch. The first is the analytics mode, where a simplified version of the environment is shown for better visibility of the idioms. The second is the realistic mode, where dams and surrounding areas are represented with photorealistic (Chin, 2023) characteristics (Fig. 30.14). To achieve a higher level of graphical fidelity, in addition to the mesh reconstruction methods used for T2, higher-quality textures were used for both the dam structure and the surrounding areas. Likewise, more accurate materials and lighting mechanisms were used for the VR scene. The development of the T3 environment also used the more advanced Unity's high-definition render pipeline, which prioritizes graphic quality and allows the effective application of methods such as ray-tracing (Formella & Gill, 1995). In this mode, water and temporal dynamics representations were introduced to increase situatedness and the sense of presence. The temporal dynamics include an accurate simulation of the Sun's (and Moon's) position for a specific time and day of the year (Fig. 30.15). The upstream water height is also based on historical data, depending on the date being analyzed, and can be directly controlled to reflect different magnitudes of hydrostatic loads (Fig. 30.16).

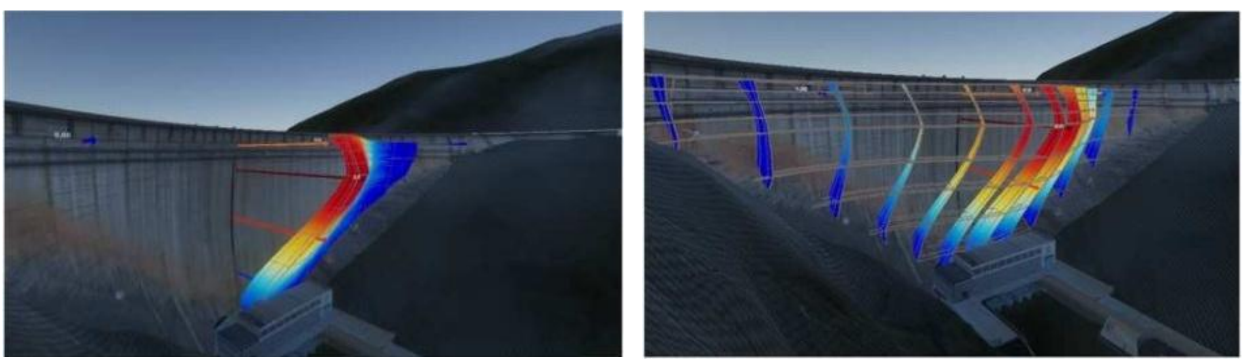

FIGURE 30.13 T3 offers advanced analytics functionalities. (left) Representation of measured displacement vectors together with spatial heatmaps of the theoretical displacements. (right) Segmentation of idioms, showing a representation of displacements in the theoretical structural construction joints.

FIGURE 30.14 T3 realistic mode consists of a photorealistic representation of the dam featuring high-quality textures and lighting.

FIGURE 30.15 T3 realistic mode simulates temporal dynamics and accurately depicts the Sun's (and Moon's) position for specific times and days of the year.

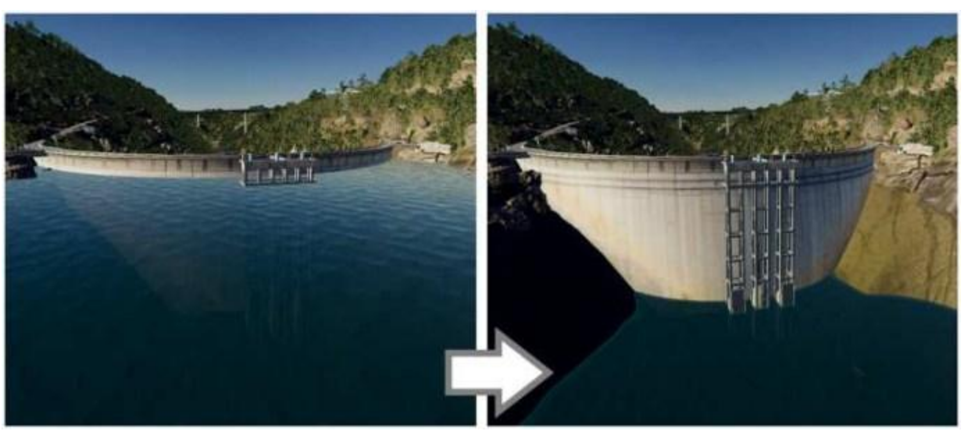

FIGURE 30.16 Upstream water heights are depicted based on historical data, depending on the date being analyzed, but they can also be directly controlled to analyze the dam's theoretical behavior for different magnitudes of hydrostatic loads.

30.3.4 Challenges and outcomes

Developing the three prototypes described early in this section was associated with significant challenges. These challenges included hardware-related aspects and issues with model construction. They also included difficulties associated with versatility, namely the capability of extrapolating the tools' functionalities to different dams. Adoption resistance based on institutionally ingrained digital culture aspects was also taken into account.

The challenges related to the limitations of existing hardware had distinct facets for the AR (T1) and VR (T2, T3) prototypes. The effectiveness of AR screen-based visualization using tablets and smartphones is highly dependent on the quality and resolution of the device's camera. Indeed, lower-resolution cameras do not allow for efficient use of the adopted tracking method (based on comparing the video feed with pre-captured images of the dam structure), resulting in the instability of the virtual elements superimposed to reality. Adopting the image targets method implies collecting high-quality seed images, preferably using the same device. Most importantly, tracking stability is highly dependent on the quality of the live feed produced by the device's camera during on-site operation.

Field testing of the prototype also showed that even when using high-quality cameras, the tracking quality is significantly influenced by weather conditions and the time of day (e.g., low visibility due to fog or the distinct shadow patterns produced on the downstream faces of dams). For the addressed case study, the Cabril Dam, this limitation was hindered by using multiple seed image targets. These image targets corresponded to different levels of luminosity and shadow coverage (Verdelho Trindade et al., 2019).

For the VR off-site prototypes (T2, T3), hardware-related challenges were mainly limited to the inherent comfort of device use. Indeed, wearing HMDs for long periods can result in head discomfort. Prolonged use of VR HMDs can also result in symptoms of motion sickness (Chang et al., 2020). These limitations, however, are likely to be minimized by advances in HMD ergonomy and performance (e.g., wider fields of view and higher refresh rates) (Saredakis et al., 2020).

Model construction was another critical challenge concerning the development of immersive situated experiences. There was no such necessity for the AR on-site prototype, as the actual physical dam was used. However, to apply the off-site VR prototypes to the case study of the Cabril Dam, realistic 3D models had to be built to ensure a proper sense of presence and situatedness. The construction of these realistic models implied laborious stages, which enabled the transformation of base point clouds and photos into photorealistic 3D models.

SHM applications developed with the specific characteristics of a single structure in mind will hardly be useful. As such, the tools were designed to be as versatile as possible. While the 3D models of the dams themselves are too specific to be easily typified, other aspects such as the interface, the sensor positioning, the SHM data, and the water bodies' dynamics are more easily generalizable. With that objective, specific mechanisms were implemented that would allow this generalization. These mechanisms include e.g., the programmatic positioning of sensor networks and water bodies.

Lastly, a fundamental challenge was the fact that the use of 2D screens and Windows, Icons, Menus, Pointer (WIMP) interfaces were deeply ingrained in LNEC workflows. Such an aspect is transversal to companies and institutions across different industries. Nevertheless, CDD was very receptive to integrating new visualization paradigms into their workflows. While recognizing the practicality of current desktop applications, their dam engineers acknowledged the potential benefits that XR technologies can bring. They pointed out that on-site applications like T1 simply do not have a conventional counterpart. T2 and T3 were shown to be beneficial for contextualizing structural data in the scope of dam structures while providing an engaging experience.

T1 and T2 were also evaluated through user studies with domain experts at LNEC. System performance, usability, and dam safety control suitability were addressed in these studies. The participants were asked to complete predefined tasks (based on actual dam safety control tasks performed at LNEC) and then to fill out system usability questionnaires. The results (Verdelho Trindade et al., 2020; Verdelho Trindade et al., 2019; Verdelho Trindade et al., 2023) showed that for similar tasks T1 had significantly better performance than T2 both in what concerns the task completion times and the number of mistakes made by the participants. Regarding usability, T1 had a marginal but consistently higher score than T2. These results seem to show that framing data directly over the object of analysis, using the AR/immediate approach, may positively impact performance and user preference. A follow-up user study with domain experts is currently being carried out on how the increase in visual fidelity and representation of data directly over the dam model, addressed with T3, compares to the lower fidelity proxied approach (T2), the immediate approach (T1) and a conventional methods' baseline.

The developed applications were intended to bring a new dimension to dam safety control visualization processes within CDD at LNEC. Although they were just the first prototypical approach, relevant feedback to developing full-fledged applications was collected. The user experience evaluation carried out with the prototypes revealed consistent positive usability across the three developed tools. The users noted, for example, how (T1) "the interface menus and icons are intuitive" and how (T2) "comfortable to use" they were. Users highlighted the realism and visual quality of the models. One user noted how close the experience was (T3) to "being physically present at the location". The analytics functionalities of the prototypes were equally considered valuable, especially as a complement to the still more robust desktop applications. In this regard, a user reported that the immersive exploration of data represented directly over a model of the structure (T3) offered a "way to better understand the spatial distribution of numeric magnitudes". Another user highlighted how the segmentation feature (T3) was "useful for obtaining insights about singularities within the structure's behavior".

30.4 Guidelines

Five consecutive stages for building SHM XR applications can be individualized: conceptualization, design, implementation, testing & evaluation, and integration. This section consists of the systematization and discussion of a set of guidelines tailored for each of these stages. This set of guidelines was established based on the bibliographic analysis carried out in Section 30.2 and the authors' personal experience, including the case study described in Section 30.3.

30.4.1 Conceptualization

The conceptualization stage is crucial to correctly identify where and how XR technologies can be applied to address a specific SHM-related problem. To that end, a clear objective and purpose (e.g., training, analysis, or collaboration) for the application have first to be established. That process has to be carried out with the target audience in mind. As such, it is crucial to understand who the end users will be. Their role within the SHM domain range will help tailor the application's complexity, content, user interface, and particularly the level of abstraction in information visualization functionalities. This initial stage is also adequate to select the range of XR hardware that will better serve the purpose of the application. Factors such as motion sickness, navigation, interaction methods, and the physical space needed should also be carefully considered in this stage. The set of possible synergies between XR and other computational technologies within the scope of the SHM application should also be defined. In that ambit, user experience and interaction modes should be taken into account.

30.4.2 Design

The design stage defines how the XR application will work, look, and support user interaction. In that scope, the user interface should be carefully planned to offer an intuitive and easy way to navigate in a 3D space. Aspects such as the choice of user interface diegetic elements (elements integrated into the virtual world) and non-diegetic elements (elements overlaid on the user's view) must be considered. The resulting user experience should be effective, comfortable, and engaging. It should also be inclusive and accessible to users with different needs.

Interaction design (Höök & Löwgren, 2021) is another critical component at this stage. How users interact with virtual objects within virtual or augmented environments is key to a performing application. In order to take advantage of the virtues of XR-powered environments, interaction should be as natural as possible. With that objective, hand gestures, voice commands, and gaze-based interactions should be preferred over more conventional modes of interaction. Likewise, feedback should be rich, immediate, and informative. Feedback in XR environments should include compelling and high-quality audio and visual components, as well as other types of feedback, such as tactile, olfactory, thermal, proprioceptive, and vestibular (Gibbs et al., 2022).

The design process should be iterative, allowing successively improved low and high-fidelity application prototypes to be closer to the intended objectives. This iterative process allows critical information about the application to be scrutinized even before the implementation occurs, saving time and resources.

30.4.3 Implementation

It's at the implementation stage that the conceptual and design plans are put into action to produce the actual application. At this stage, ideas and designs will be translated into a functional XR experience, with an expected tangible impact on the addressed SHM aspect. The first step of this stage is selecting the coding language (e.g., C# or C++) and the development environment setup, including the graphical engine (e.g., Unity or Unreal). These should be chosen based not only on the application requirements in terms of compatibility and performance but also on the development team's familiarity with such tools.

The development comprehends creating or sourcing the necessary 3D models, textures, animations, and realistic physics simulations. The visual quality of such assets should be balanced with the performance requirements while ensuring the accuracy of the data representation. An example of such a challenge in optimizing for performance without compromising quality is the modeling and representation of large-scale terrains or complex and intricate civil structures. Techniques such as real-time dynamic level of detail rendering (Ramos et al., 2012) allow the model to be represented with less detail as the user moves away from the structure or terrain surface (therefore saving computing cycles).

It is also at this stage that XR interactivity implementation takes place. This process consists of coding the interaction possibilities of the users as they move through the immersive environment. This interaction comprehends the implementation of aspects such as locomotion in the VR space or physical movement tracking in AR. It also includes coding the possibility of direct interaction with virtual objects. An example of such interactions is the selection mechanism of a specific sensor in a bridge pillar in the XR environment to retrieve its measured structural data. These mechanisms should be implemented considering VR and AR-specific challenges, such as motion sickness prevention or tracking precision. Likewise, for applications that include collaborative environments, appropriate networked mechanisms should be implemented to ensure performance, low latency, and correct user experience during multiuser sessions. The same is true when the application includes digital twin characteristics. In that case, an appropriate real-time connection with the real structure dynamics must be implemented. Such implementation must consider aspects such as state synchronization between the model and the real structure using secure and stable communication channels.

SHM data sources should be seemingly integrated to ensure accurate and agile data representation. As such, algorithms for real-time data processing and visualization within the XR environment should be implemented. As we have seen previously, data should be directly represented over the structure being analyzed (or a virtual model of that structure) to ensure appropriate situatedness.

30.4.4 Testing and evaluation

Before integrating the application in SHM workflow, thorough testing needs to be carried out. Functional testing (Elssamadisy & Whitmore, 2006) is used to ensure that the application's features work as intended. It comprehends interactions, user interface elements, and environment dynamics. Usability testing (Hertzum, 2020) with end-users allows the collection of feedback and the identification of frailties in the application, as well as aspects that could be improved. Performance testing (Esteves & Brito, 2023) will allow the evaluation of the application's performance across different XR hardware. Such testing procedures will ensure a high frame rate at runtime, which is crucial for preventing the downsides of XR environments, such as motion sickness.

The application's compatibility with the range of devices that will be used in the real-world use cases for which the application was developed must also be tested. Examples of such hardware include different types of XR headsets, controllers, and operating systems. The application's accessibility should also be tested to ensure that users with disabilities can use it effectively. Likewise, the accuracy of SHM data representation within XR environments should be tested and validated. Adjustment and refinement should then be carried out based on testing results.

Security testing (Cayir et al., 2024) to identify vulnerabilities that could compromise user data or the integrity of the application should also be considered. Mechanisms such as data encryption and secure communication channels should be included in these testing procedures.

Applications should also be tested in real-world environments to ensure they perform well in different spaces and lighting conditions. This aspect is particularly important for on-site SHM applications that will be used in harsh and remote locations. In such settings, ensuring application stability and robustness is key. In that sense, the application's performance should be evaluated under different conditions and workloads.

30.4.5 Postimplementation integration

Integration with the existing SHM workflows should be planned as a phased roll-out, monitoring performance and user adaptation in real-world scenarios. As such, appropriate user feedback loop mechanisms, such as surveys and feedback forms, should be established. These ensure a systematic approach to collecting, analyzing, and acting on user feedback. In that process, user training should be provided to maximize the application's potential and ensure safe use.

Training protocols should be built to facilitate the transition from traditional SHM methods to XR-based methods, taking into account a set of key aspects. One such aspect is the precise definition of the specific goals of the training sessions and XR SHM skills that the trainee is expected to acquire (i.e., simple sensor localization or more demanding data analysis) (Lukowski et al., 2021). The training sessions should also be designed to meet the specific needs (Schallock et al., 2018) of different SHM roles (e.g., XR sessions targeted towards engineers should differ from those targeted towards field technicians). The same goes for the training methods, materials, and resources (Timotheou et al., 2023), as different SHM tasks will likely require distinct XR abilities.

A systematic approach and structured delivery of the different training stages should be considered (Yimam, 2022). The initial stage should be oriented towards familiarizing the user with XR technology. At this stage, safety and ergonomics training should also exist to prevent physical strain and accidents resulting from the use of XR technology (by taking advantage, e.g., of anti-collision mechanisms[5]). The following stage should consist of hands-on training sessions (Li, 2022). This stage should include in-depth training on the SHM scenario using the corresponding XR application features. Guided practice sessions with real-world scenarios should take place in order to build familiarity and confidence among the users on the XR systems and devices used. The sessions should be role-based (Merriman et al., 2023) with distinct tasks and responsibilities.

As previously mentioned, feedback mechanisms should be in place in all training stages so that the training's effectiveness can be assessed (Shewchuk et al., 2023). These mechanisms will also provide valuable insights for possible follow-up sessions. Likewise, they can serve as a base for developing updates to the XR systems. Furthermore, they will help identify common technical problems that should be addressed by providing regular updates to the users.

The application's impact on SHM use cases should also be monitored, adjusting the initial implementation as necessary. This update process should also consider the emerging SHM needs and technological advancements. With the experience gained with the base application, new opportunities can also be explored for further integration of XR technologies in SHM processes. An application's development

[5] Such as Oculus' Guardian System: https://developer.oculus.com/documentation/native/pc/dg-guardian-system/

roadmap should be implemented based on user feedback and performance data. Such mechanisms provide an appropriate plan for future expansions that can complement or leverage the current application.

30.4.6 Balancing Costs and Benefits

When conducting cost-benefit analyses for specific XR in SHM implementations, two sets of factors should be considered and balanced. The first set concerns initial setup costs for the different stages, including development, deployment, and training. The second consists of the possible long-term benefits, including cost savings, that result from the use of XR compared to conventional methods (Pöhler & Teuteberg, 2023).

A substantial share of the initial setup costs involves acquiring hardware and software (Mohammadi & Garrido Martins, 2024). In the development stage, the investment in devices needed for implementation should be considered. These include not only HMDs (AR, VR, or hybrid) or mobile touch devices (e.g., smartphones, tablets) but also XR-ready computing equipment (workstations). The latter must be capable of processing real-time data from XR devices and running advanced simulations and analyses. In some cases, hardware costs may also include specialized equipment to collect data that will serve as a basis for building 3D models of real structures, such as UAVs for photogrammetry and Light Detection and Ranging (LiDAR) scanners (Luleci et al., 2022). The XR-dedicated equipment used for development can potentially be reused in the operational stages. For certain situations, namely on-site XR applications, rugged equipment should be preferred, as addressed in Section 30.1. And regarding software costs, these can include licenses for XR development tools, plugins, or graphical assets. A notable example is advanced computer vision SDKs for accurate AR tracking.

Other setup costs include the ones related to deploying and integrating the XR systems with the existing SHM infrastructure. These costs can result from, e.g., specialized SHM-related sensors that can talk directly with the XR system or, in alternative, devices that can serve as an interface between conventional sensors and the XR system. They can also comprise specialized networking equipment that allows secure, high-bandwidth communication on-site. Likewise, they may incorporate testing and calibration equipment to ensure data collection and analysis accuracy (Haider et al., 2022). Additional costs should also be considered for training engineers and technicians to use XR equipment and system-specific features. These costs might include creating documentation and training materials, such as implementing training-specific versions of the XR SHM system.

Possible benefits resulting from the deployment of XR in SHM include improvements in structural monitoring processes, namely in predictive maintenance. For example, wearable XR equipment allows for continuous and real-time data collection of structural conditions on-site, which can contribute to the early detection of issues. This type of proactive mechanism leads to reduced operational costs resulting from decreased downtime (Bakhoum et al., 2023).

XR can also enhance workers' safety, for example, by allowing inspections to be done remotely. By reducing the need for engineers and technicians to be physically present on-site, XR systems can reduce their exposure to possible on-site hazards. They can also hinder risks and costs related to traveling to hard-to-reach locations (Delgado et al., 2020). XR can equally improve SHM operational efficiency by helping streamline data analysis processes. XR systems are capable of providing actionable insights in a more natural and intuitive way than conventional means. And the seamless integration of XR technologies with

SHM processes can contribute to workflow optimizations, resulting in increased productivity (Senanayake et al., 2023).

The balance between XR's costs and benefits should be quantified based on relevant tangible metrics. These metrics include the cost savings that might result from the preventive maintenance mechanisms introduced by XR (Girgin et al., 2024). They also include the reduction of inspection and travel costs that derive from remote monitoring. In that sense, safety improvements, particularly the reduction of accidents, should also be taken into account. Likewise, operational efficiency improvements, namely arising from enhancements in data analysis, with benefits in supporting decision-making, should be considered. A more general but less immediate metric, the increase in the lifespan of structures originating from XR-enhanced processes, should also be taken into consideration.

30.5 Future of XR in SHM

The dissemination of XR technologies in the SHM domain offers unprecedented opportunities for visualizing, analyzing, and interacting with structural data, sometimes in previously unattainable ways. This integration promises to transform how engineers and technicians monitor and assess the health of structures. As we have seen, this technological symbiosis has a wide range of applications, from bridges and buildings to tunnels and dams. Due to the demonstrated advantages of this symbiosis, moving forward, SHM will most likely be intimately connected with the rapid evolution of XR hardware and software.

Industry 4.0 (Adriana Cárdenas-Robledo et al., 2022) and, in particular, its AEC conceptual sub-category, Construction 4.0 (Sawhney et al., 2020), have determined a pathway of integration of a multitude of digital tools across the construction ecosystem. It is in all likelihood the SHM workflows will evolve within that pathway. As such, XR will not be used in isolation but instead integrated with other existing and emerging technologies. A critical facet of this integration will be in the scope of a more intimate connection between the digital and the physical through cyber-physical systems (Tyagi & Sreenath, 2021).

This tendency to integrate XR with other digital technologies in the scope of SHM can be exemplified in the materialization of digital twins for immersive environments. As we have seen, the adoption of this type of system in SHM XR applications has been growing significantly. Its implementation generally requires the use of realistic digital models of the real structure. As such, the future of XR will necessarily involve the development of increasingly detailed models that will ensure high levels of situatedness and presence. Thus, the model construction process will increasingly use technologies such as BIM and UAVs equipped with laser scanning.

In addition to reproducing their physical counterparts' geometry and visual aspects, digital twins mimic their context and behavior. This functional mimicking in the scope of XR systems will require increased use of advanced sensing, which can be integrated both in existing systems with Internet of Things (IoT) (Nagajayanthi, 2022) technology and personnel through wearable sensors. Likewise, actions in the virtual model within the XR environment must also be able to be reproduced in the physical referent. That will be achieved by an increased use of smart actuators in existing control systems.

Last- generation wireless network technologies will be increasingly used for an appropriate, safe, and timely synchronization of data between the XR digital twins and their physical counterparts. The data exchange will tend to be made within the scope of cloud-based common data environments. These will support advanced SHM use cases such as structural inspectors on-site using AR headsets and off-site managers using VR headsets' ability to work seemingly in common, collaborative XR environments.

These remarkable possibilities will come at a cost in terms of data volume. As a result, XR applications will have to increasingly be developed with big data mechanisms in mind. In that scope, artificial intelligence (AI) technologies, which have been adopted across all industry sectors, will also be progressively adopted to make XR SHM applications smarter. As we have seen previously, AI has been studied widely in XR SHM research for a number of practical purposes. Closer integration of XR and AI, two technologies that have seen an explosion in popularity in recent years (Babina et al., 2024), will predictably also take place.

30.6 Conclusion

This Chapter started by analyzing how XR in SHM is currently being addressed in scientific studies. We also described a case study of implementing VR and AR technologies in dam safety control. Based on existing work and the author's personal experience, particularly in the described case study, a set of guidelines for developing XR applications for SHM was presented. Finally, the future of SHM with XR was discussed and exemplified in terms of the scope of developing digital twins.

As has been highlighted, XR has transformative potential in the SHM domain. It can potentially enhance the accuracy, efficiency, and safety of structural inspections and maintenance tasks. This enhancement is especially relevant when XR is applied within the scope of other digital technologies, such as intelligent sensors and actuators. This integration possibility of XR with other digital technologies may offer unparalleled opportunities for the future of the SHM field.

XR technologies are also multifaceted. This characteristic allows the most appropriate technology to be selected according to the SHM scenario. VR allows engineers and technicians to immerse themselves in virtual environments that simulate the real-world structures they aim to address, both in aspect and dynamics. Such virtual environments hinder the physical constraints of accessing the structures in person. AR can overlay relevant digital information in the real world. This possibility enables the immediate situated visualization of structural information.

The combined use of these technologies for SHM data analysis, known as Immersive Analytics (Dwyer et al., 2018), has been known to improve analytical thinking and support decision-making. This type of technology's collaborative aspects also enable specialists to share insights and make informed decisions without the need for physical presence. Such characteristics are especially valuable in challenging or hazardous environments.

However, the application of XR technologies is not without its challenges. Complex applications require high computational power, sophisticated sensors, and robust software platforms. Due to its specificity, the implementation of XR in the SHM scope often requires dedicated personnel training. However, the fast evolution of XR software and hardware in recent years will predictably hinder many of the present disadvantages of applying these technologies. Its drastic price reduction has also determined its increasingly widespread adoption. This adoption will inevitably lead to the familiarization of its use by both SHM experts and the general public.

This continuous evolution of XR technology, coupled with increased interest from the AEC industry stakeholders, suggests that its integration into SHM workflows will likely deepen. Its combination with emerging trends, such as AI and machine learning, is poised to further enhance the capabilities of XR SHM systems.

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