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Heritage ++, a Spatial Computing approach to Heritage Conservation

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Abstract

Historic structures are affected by numerous degradation processes driven by a complex system of interconnected and mutually influencing factors. Preserving these monuments is a multidisciplinary endeavour that extends beyond one-time interventions, necessitating a comprehensive methodology that involves various stakeholders, expert consultations, monitoring tools, and impact assessments. Limitations arise due to communication barriers and difficulty in translating and transferring experience among disciplines, often compromising the collective ability to define the best possible conservation strategies.

Recent advancements in 3D modelling and data management technologies offer collaborative platforms for information sharing. However, the complex interfaces of these tools often limit their accessibility, making them exclusive to specialists. Integrating Spatial Computing could address these challenges by fostering intuitive engagement and enhancing accessibility and depth in interdisciplinary interactions. This letter outlines initial efforts in using spatial computing to tackle the challenges of built heritage conservation and presents a vision for its future development.

Keywords: Built heritage conservation; Spatial computing; Multidisciplinary collaboration; Extended reality (XR) applications.

1 Introduction

The evolution of heritage conservation has been influenced by a range of approaches and philosophical shifts over time [1]. The collection of information, initially intending to preserve structures for their utility and practicality, evolved in complexity as the philosophies of conservation advanced. In the 18th century, modern restoration as it is understood today was born, gradually increasing the emphasis on historical notions related to the preserved structures [2]. A prominent theory from this period, 'stylistic restoration,' exemplified by Eugene Viollet-le-Duc, referred to restoring structures to their assumed original state, based on historical research. This evolved into the anti-restoration movement, advocated by Ruskin and Morris, which stressed the importance of authenticity and context [1]. In addition to technical drawings, photography became an important tool for documentation and data collection [2].

The development of international guidelines throughout the 20th century, like the Athens Charter (1933) by the International Congress of Modern Architecture (CIAM), and the Venice (1964) and Burra (1979) Charters by ICOMOS, expanded the scope and focus of conservation to address several aspects of heritage in a more holistic sense. Building on these, the next shift promoted preventive conservation strategies, a term first coined in the 1970s. It prioritises maintenance and systematic monitoring to mitigate deterioration before it necessitates repair, reflecting a broader understanding of heritage preservation [3]. The introduction of this concept underscored the importance of cyclic data collection and management of extensive information, leading to the development of new

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methodologies and tools. *Monumentenwacht*, developed in 1973 in the Netherlands, pioneered the preventive conservation of built heritage. It provides regular inspections, reports, professional references, and manuals for the maintenance of built heritage [4]. The related organisation has provided a base for the development of similar methodologies elsewhere (i.e., Maintain our Heritage in the UK, 1999, DenkmalWacht in Germany, 2004, Bygingsbevaring in Denmark, Mamég in Hungary, and so on).

Today, driven by the goal of sustainable development, conservation practices have evolved to incorporate advanced tools like Heritage Building Information Modelling (HBIM), Extended Reality (XR), and Geographic Information Systems (GIS). Recent projects on this topic such as HeritageCare involve collaboration among teams from Spain, Portugal, France, and Italy [5]. However, despite such initiatives having already existed for several years, their impact unfortunately remains rather localised.

More importantly, the ever-evolving field of heritage conservation is now undergoing a technological paradigm shift, moving towards more proactive and data-driven methodologies. This new era emphasises efficient access to information, interaction, and analysis of vast and diverse datasets to support decision-making. In this regard, emerging technologies like Spatial Computing, Artificial Intelligence (AI), and Machine Learning (ML), promise to improve the accuracy and efficiency of documentation and analysis of historic structures, enhancing the effectiveness, depth and quality of interdisciplinary collaborations. This letter aims to lay out this potential by introducing emerging applications in built heritage conservation, in an approach we term Heritage++. While examples mainly pertain to stone-built monuments, the main principles presented are valid much more broadly.

2 Challenges in the conservation of built heritage

This section outlines the current challenges of built heritage conservation, especially related to the degradation of building materials.

2.1 Spatial and contextual nature of conservation

The deterioration mechanisms affecting building materials are influenced by an interplay of intrinsic and extrinsic factors [6] [7]. Intrinsic factors include the material's physical and chemical properties. The lithology of the stones is also a significant factor moderating the intensity of alteration. Extrinsic factors encompass environmental conditions like climate and pollution levels in the monument's vicinity. Constant interaction between these factors is most often the main driver for degradation [8].

A majority of the damage mechanisms affecting built heritage sites, including clay swelling, dissolution, freezing, salt crystallisation, atmospheric pollution, and biodegradation, occur in the presence of water [9]. This water can originate from various sources like groundwater, precipitation (run-off and wind-driven), surface water [10], aerosols and air moisture. Additionally, factors such as wind and sun exposure can also be key vectors of degradation. Therefore, at the larger scale of a monument, the location and orientation of elements as well as their exposure to microclimatic conditions play an important role. The consequence is a differential distribution of the types and rates of alterations over the monument, and hence, no one-size-fits-all solution can be prescribed for their conservation [11]. This complexity further increases because many degradation processes may exhibit similar forms resulting from distinct underlying mechanisms. Thus, degradation patterns alone may not suffice for identifying the cause of damage, necessitating additional data for more conclusive diagnostics [12].

Given the above, a proper spatial understanding of the monument is necessary to reliably assess the damage mechanisms at stake, which remains a major challenge due to the mere uniqueness of each context. Currently, documentation and related studies tend to be fragmented, lacking the seamless integration needed for such comprehensive analysis. Therefore, a centralised platform is necessary for the integration and visualisation of data across multiple scales- from a global overview of the monument to local microclimates and material microstructures, as schematically shown in Figure 1.

2.2 The role of intuition and multidisciplinary dialogue in problem-solving

Despite the complexity of challenges, domain specialists leverage years of experience and tacit knowledge [13], [14] to navigate the intricate and often contradictory demands of heritage preservation and find a balance between qualitative and quantitative factors in decision-making. This intuitive knowledge is especially valuable for addressing the "wicked" problems [15] that characterise this field. However, despite their importance, these insights can be challenging to be systematically documented and transferred within a multidisciplinary context. Furthermore, the collaboration between disciplines such as architects, conservators, historians, and structural engineers, to name a few, is not always easy. For example, there is a significant gap observed between material sciences studies and conservation practice [16], [17], with exchanges often remaining extremely qualitative and facing, in particular the difficulty of sharing core "experience-based" knowledge and/or domain-specific "intuition". Many of these exchanges happen orally, but are also supported by drawings, reports, photographs, data and more [18]. This highlights the need to identify, organise and formalise the intuition of experts in this field and further enhance it through improved accessibility and interaction with the available critical data.
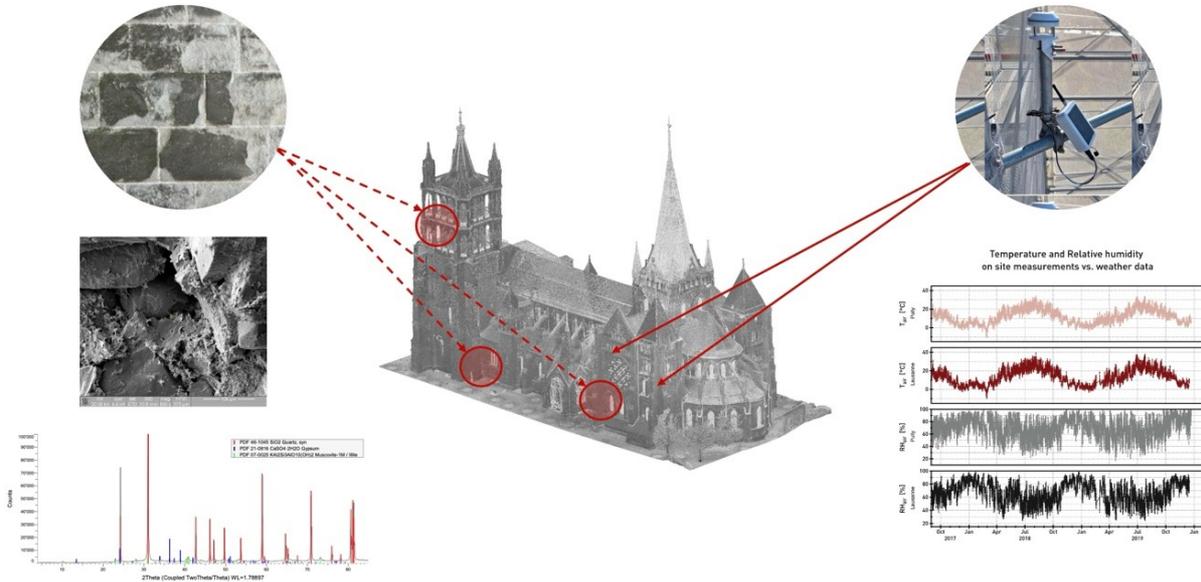
Figure 1. Schematic illustration of the spatial and multiscale nature of the challenge in assessing degradation mechanisms that a monument may suffer from to define the conservation measures it will most benefit from. This example illustrates the three-dimensional relations of factors such as stone types (petrology, microscopy, mineralogy) and microclimatic conditions (wind direction, temperature, humidity, and driven rain,) at the Lausanne Cathedral and how they are currently visualised.
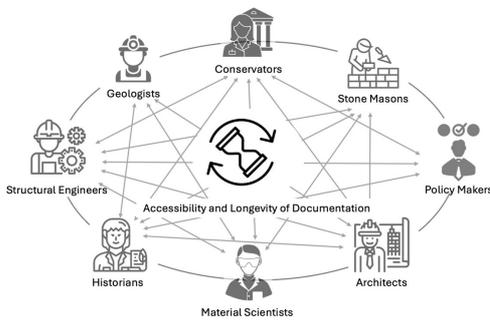

Figure 2. Schematic representation of the need to facilitate communication among the various disciplines involved in conservation, and to do so over time allowing for new information and/or interpretations to flow into the system.

A further challenge in this multidisciplinary endeavour lies in the diversity and complexity of data sources in heritage documentation [19] which can hinder mutual understanding among disciplines. However, incorporating "storytelling" through visualisations, in particular interactive ones, can help bridge these gaps, making information more comprehensible and usable for all stakeholders. As illustrated in Figure 2 efficient collaboration requires not only establishing multidisciplinary links but also ensuring that data is accessible and periodically updated. This allows for simultaneous interdisciplinary communications while accommodating new findings, ongoing monitoring, and changing socio-political contexts. To facilitate this, current methodologies must evolve from static and "screen-locked" content to more interactive, "world-locked" [20] content.

In this regard, the integration of spatial computing technologies with traditional 3D modelling and information management can offer some promising solutions. To do so, spatial computing creates interactive experiences in both real and digital environments by bringing together technologies like AI, XR, and Global Positioning Systems (GPS) [21]. The following section defines the current understanding of spatial computing and its fundamental elements. It explores additional technologies that, while not traditionally associated, can empower decision-making in heritage conservation.

3 The potential of spatial computing in built heritage conservation

3.1 Spatial computing and its current applications

Spatial computing can be defined as a collection of ideas and technologies which understand, communicate, navigate, and respond to places in our physical world [22]. It is an advanced form of digital interaction that merges physical and digital spaces, enabling computers to understand and respond to the physical environment in real time. The term was first coined by Simon Greenwold, referring to the interaction between a machine and a human where the machine can retain and manipulate referents to real objects and spaces [23]. Initially emphasising the capture and analysis of the physical space through GPS, Remote Sensing [24], and other Spatial Information Systems [25], today, Spatial Computing has evolved to include AI, Internet of Things (IoTs), Mobile Computing, Robotics, and XR, that integrate our physical

world with the digital world. These technologies have empowered a new generation of User Interfaces (UI) which are now evolving from screen-based interactions to more immersive and spatially aware ones at the thresholds of the virtual and real environments [26].

The term XR includes widely used platforms, Augmented Reality (AR), which provides digital information overlayed on physical objects in the real world and, Virtual Reality (VR), which enables highly immersive environments and experiences taking place in a completely digital world. Spatial Computing, being an overarching concept, encompasses AR and VR while transcending them to focus on creating more realistic and intuitive interactions. [27]. To achieve this, a combination of enabling technologies such as GPS, AI, XR, IoTs, 5G, Cloud/Edge Computing [28], Blockchain, etc, are employed [26]. These technologies, together, provide intuitive multi-modal interactions in the real world. Headsets such as Apple Vision Pro, Microsoft Hololens2, MetaQuest3, and MagicLeap2 currently support commercial and industrial applications of these advancements [26]. Additionally, developments in wearable devices supporting AR such as xReal, Ray-Ban meta smart glasses, Focals, and meta-Orion show a glimpse into the future of this technology [29].

The evolution of Spatial Computing has been shaped by two key factors: the growing number of applications of the technology and the development of supporting platforms [22]. Hence, applications play an important role and can direct innovations in the technology as well as its supporting platforms. In addition to the Gaming industry, several fields have already started employing Spatial Computing to augment their workflows. The healthcare industry, being one of the most important application fields of this technology, uses it for surgical navigation, medical training or telemedicine. In education, spatial computing enables interactive learning experiences, simulated lab experiments, and virtual field trips. Other emerging fields exploring spatial computing applications include Manufacturing, E-Commerce, Architecture, Tourism, Transportation, and Military [26]. Emphasis is shifting to enhancing these capabilities for real-world applications to equip domain experts with useful information in their decision-making process.

Many of the enabling technologies behind Spatial Computing have already found their way into Cultural Heritage, namely, GIS, LiDAR, Remote sensing, Computer graphics, AI, VR, and AR. However, the use cases remain fragmented due to the above-mentioned context-specific nature of conservation projects. In addition, most of the existing workflows lack a long-term impact due to limitations in standardisation [18], [30]. We therefore need to start thinking in a direction where Spatial Computing can be integrated into a pragmatic workflow to harness its potential as the next generation of UI to durably support collaborative problem-solving.

3.2 Tackling the challenges of heritage conservation

As discussed previously, interdisciplinary collaborations lie at the heart of heritage conservation. Professionals use various methods for data analysis and representation and thus require different platforms for visualisation. This field often requires on-site inspections, which can be improved by AR. However, additional sources of information must be consulted, such as data in tables and plots are better visualised on screens, realistically in an office. Thus, effective decisions-making in a collaborative environment can require a back and forth between both, which is normally not possible or at best extremely inconvenient. The application of spatial computing in this context will provide a simple solution, allowing teams to access and visualise data on multiple scales, as well as different modes.
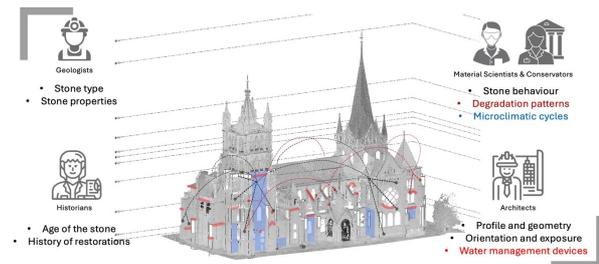

Figure 3. Schematic illustration showing the power of spatial projections for visualisation and correlation of different datasets in interdisciplinary problem-solving.

While platforms like HBIM have proven their potential as a collaborative tool for data integration, their capabilities can be significantly expanded. HBIM currently excels in providing a spatial understanding of conservation challenges by connecting various datasets simultaneously. However, the models risk being limited to a single use case due to a lack of useful data and complex interactivity [30], [31]. With the integration of spatial computing technologies, HBIM can overcome these limitations to become an even more powerful tool for built heritage conservation. This combination would aid in the comprehensive understanding of matters like degradation mechanisms affecting a historic structure and intervention quantification, offering a multiscale view of the monument and insights into specific aspects such as stone properties, water distribution, and so on.

Existing AR and VR applications in heritage conservation primarily focus on enhancing tourist experiences, such as immersive museums and virtual tours [32], [33]. Several projects by [34] explore the Scan to BIM process and the adaptation of the HBIM models for various XR environments, fostering immersive and interactive cultural heritage tours. One of the notable initiatives, the HeritageCare project, developed a mixed-reality-based platform allowing professionals to anchor observations and annotations in the HBIM model during the inspection of a structure [35]. Despite its great potential, the project encountered challenges in terms of the accuracy and usability of the device. These efforts give a glimpse of the exciting possibilities in the future of conservation, at the same time, they underscore the necessity of further research to refine the technology and to design efficient workflows for its application.

With ongoing advancements in Spatial Computing, there is growing potential to integrate these technologies into heritage conservation. For instance, as illustrated in Figure 3, these tools can spatially project interactive maps visualising results produced by field experts and thereby enable remote consultations, collaborative analysis, and consequently, efficient decision-making. To fully unlock these capabilities, it is essential to explore the role of spatial computing technologies beyond academic and entertainment purposes, and instead apply them in practical scenarios.

Furthermore, there are opportunities to explore the integration of AI tools like Large Language Models (LLM), Computer Vision, ML models and so on with HBIM and XR to document intuitive knowledge and support conservation experts as a "copilot". These tools can facilitate a deeper understanding of the challenges faced by historic structures, enabling multidisciplinary teams to identify, analyse and address problems from diverse standpoints. With this vision in mind, several ongoing and planned projects aim to integrate Spatial Computing and related technologies into conservation workflows. The following section highlights a couple of ongoing initiatives under the Heritage++ approach to address different challenges of built heritage conservation.

4   Steppingstones to Heritage++

The diversity of factors behind degradation demands locally tailored solutions based on clear understanding of the structure's context. The integration of HBIM with Spatial computing and AI tools offers an opportunity to leverage the spatial nature of this challenge by storing and visualising the critical information. Furthermore, decision-makers often face challenges in assessing the long-term performance and full implications of conservation interventions. Spatial computing and XR in particular can address this by offering onsite multi-scenario visual overlays of the proposed interventions. Such capabilities can improve impact assessments by taking into consideration factors like reversibility and intrusiveness, implications on the authenticity and integrity, and any risk posed to the associated values. In doing so, it will allow targeted interventions, thus, greatly reducing costs, time and efforts while preserving the structure and its significance.
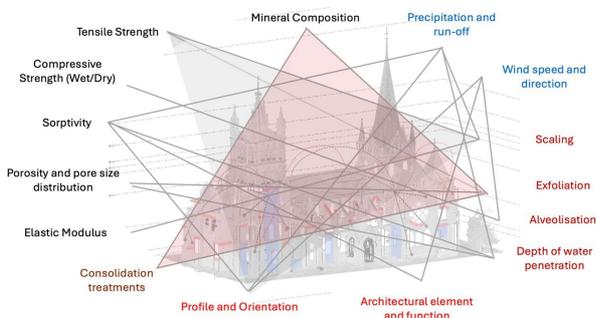

Figure 4. Schematic representation of the correlating information for analysis of degradation.

With that overarching vision in perspective, we are currently developing Heritage++ as a methodology that focuses on understanding different degradation mechanisms through

documentation and rationalisation of the interactions between stones and water. As illustrated in Figure 4, solving problems related to degradation of built heritage is highly dependent on uncovering interconnections between the intrinsic properties of the material and external environmental conditions that give rise to different damage mechanisms. That said, as of today, reliable use of ML algorithms in finding these correlations is not possible due to limitations arising from a lack of consistent datasets and a well-structured approach [30]. Hence, a comprehensive methodology is required, starting with the curation of databases connected with geometric information, followed by augmenting access and visualisation, and finally, their analysis to unravel how combinations of different factors condition the type and extent of degradation. Other, less data hungry, approaches than ML, such as Physics Informed Neural Networks (PINNs) may then also be considered, as in other fields of building materials [36].

To develop this methodology, the Lausanne Cathedral has been selected as a reference monument. With the commencement of its construction dating back to the 12th Century CE, it is one of the largest Gothic monuments in Switzerland and one of the most important in Europe [37]. Its significance, combined with its complex geometry and structure, makes it an ideal case study for this enterprise. The Cathedral's fabric is composed of various stone types, the result of centuries of interventions and restoration work [38]. This diversity, coupled with the varying microclimatic conditions affecting the structure, has led to a differential distribution of rates and types of degradation. The following sub-sections delve into various modules, within the broader framework, designed to address specific challenges associated with this case study.

4.1   Interacting with an augmented HBIM

The first steppingstone towards developing an interactive data model is the integration of relevant databases with 3D geometry using HBIM. In the case of the Lausanne Cathedral, 3D modelling was conducted referring to point clouds and photogrammetric data [39], combining both medium and high Geometric accuracies (GA) and unique Identifiable Objects (IO) to address specific conservation challenges [30]. External databases with information concerning stone properties relevant to durability are being attached to the BIM model. Such databases are being curated to include the mineralogical and geochemical composition of the different stone types, including results from microscopy [17], mineralogy (X-ray diffraction: XRD) and elemental analysis (X-ray fluorescence: XRF) of samples from the cathedral. Building on this, information about the petrological [40], physical and mechanical characterisation is also being integrated into the model based on on-site and lab testing, and existing literature [7], [41]. Information about the age of the stone, and history of interventions is additionally being integrated to provide a temporal dimension. Furthermore, archival images and drawings will be mapped in the BIM model.

A critical question arises, how will users meaningfully interact with this data model beyond passive visualisations? In

traditional AR overlays, the interaction with real-world objects remains limited and physical spaces serve as a mere background rather than an interactive element [42]. With the next generation of Human-computer interaction (HCI), powered by spatial computing, more intuitive engagement with both the structure and its underlying data becomes possible. Tools like multi-modal Large Language Models (MLLMs) working together with XR would allow experts to query and retrieve specific information through natural language processing, making access to the data model more intuitive [43].

The integration of geospatial anchors, such as those provided by Google [44], would allow another layer of functionality by grounding digital information within real-world environments. For XR applications where the digital model is spatially linked to the physical monument, this means that stakeholders can interact with data in situ [45]. We anticipate that this emerging possibility of accessing and visualising data on-the-fly will extend the capacity for interdisciplinary work that characterises built heritage conservation. Additionally, VR visualisations can offer solutions for remote consultations by providing off-site access to the HBIM model and the underlying data.

Even more, impact assessments, which play an important role in decision-making, can also be improved using XR visualisations and simulations. A specific example from the augmented data model of the Lausanne Cathedral, involves documenting interventions for rainwater management placed on the cathedral over centuries [46]. By integrating this geometric information with data on stone characteristics, weather, and video documentation of rain events, we are analysing how effective those interventions have been in mitigating degradation. Such an approach supports more informed decisions on future conservation strategies by predicting long-term impacts and improving intervention designs prior to implementation.

4.2 Accessing monitoring data

The next essential steppingstone in this endeavour is accessing and interacting with onsite monitoring data. As previously explained, microclimate monitoring plays a crucial role in identifying the causes of deterioration and evaluating restoration interventions, as well as their durability. Although numerical simulations of climatic events like wind-driven rain (WDR) have been tested on buildings, their complexity and the peculiar geometries of cultural heritage objects often pose limitations in representing ground reality. Hence, a data-driven approach for on-site monitoring with sensors represents the most accurate method for collecting essential information about climate, such as rain, wind direction and speed, and irradiation [47].

In the case of Lausanne Cathedral, we have been focusing on the impact of water distribution on the degradation mechanisms of clay-bearing sandstones. Several sensors have been implemented on the monument including wind-driven rain panels, impedance measurements and temperature/relative humidity sensors for determining the presence of liquid water within stone blocks [48], [49].

Communication with sensors, including the reception of data, is carried out wirelessly via radio waves. The data is continuously stored in a time-series database, allowing for real-time monitoring. At a monumental scale, the collection, management, and analysis of this immense amount of climate data can become challenging. Moreover, installing sensors on monument facades is often limited due to conservation guidelines and concerns about possible invasiveness and visual impact on the monuments.

In this context, some ML models such as those explored by [50] emerge as a potential tool, allowing for a reduction in the number of required sensors while providing representative data for the entire area of interest through the integration of geometric information. Additionally, the subsequent integration of climate data with material and deterioration databases, could offer the possibility to identify the combinations of factors most harmful to the materials in question. To tie up loose ends and achieve the integration of real-life situations with laboratory experiences, a new testing facility called GRISU has been built. This facility replicates controlled, and realistic climatic events based on on-site measurements, allowing for reliable results regarding material properties and their changes [51]. Therefore, the evaluation of the strategic placements of climate sensors, as well as the digitisation and automation of data collection in formats easily integrated with 3D models, are the focus of research in this field. Here, IoT serves primarily as the infrastructure for real-time data collection.

The integration of the abovementioned data into an HBIM model makes it a central tool for analysis and decision-making. By giving a spatial understanding HBIM supports the management of incoming data from onsite sensors as well as maintenance of the sensors themselves. Again, challenges may arise due to the nature of visualisation and interaction with the collected data. This data is being accessed on a cloud-based platform in the form of several time-series graphs. We are currently working on visualising this data on building facades for on-site consultations using XR. Advanced visualisation and interaction provided by AR can be harnessed to project the resulting data combinations onto virtual models, facilitating intuitive and interactive on-site inspections, for example, by visualising the areas most exposed to damaging climate factors and the data on the material properties.

4.3 Domain Expert 2.0

Domain specialists hold essential knowledge related to monuments, offering crucial insights into the challenges of heritage conservation. However, much of this unique intuitive knowledge resulting from invaluable field experience remains undocumented due to the difficulty in capturing and transmitting it. Hence, effectively utilising multidisciplinary expertise for decision-making in built heritage conservation is both time-consuming and inefficient with traditional methods. To address this gap, a multi-modal approach is necessary, allowing the integration of on-site oral explanations with spatial data and visual evidence. Even so, this wealth of captured information, along with diverse

sources remains highly unstructured, making it difficult to analyse and extract meaningful insights.

This situation can, however, be fundamentally changed thanks to recent advances in multi-modal LLMs. Indeed, such models can ingest vast amounts of internal documentation, providing interactive interfaces—often in the form of chatbots—to enable efficient querying and navigation of complex information [52]. When combined with retrieval-augmented generation (RAG) pipelines, LLMs offer significant advantages over classical search engines by making semantic connections across diverse data sources [52]. RAG pipelines retrieve relevant documents from a database based on user queries and feed them as context into an LLM for it to generate precise and contextually informed responses. This eliminates the need for costly and time-consuming fine-tuning of LLMs on domain-specific data, allowing continuous updates to the database without requiring retraining.

RAG systems integrated with HBIM could form the backbone for storing and retrieving element-wise information about the heritage structure [53]. This approach is being explored to capture and structure domain specialist knowledge and intuition about the Lausanne Cathedral. As mentioned before, such a system could be used to query detailed information about individual elements of a building's HBIM, for example, by asking, "What do we know about element X?" and storing this response within the HBIM [54], [55]. It can be further developed to support interactive querying, such as, "Which elements of the building are most affected by weathering?"—with the system retrieving and synthesising relevant information, including visual data, and pointing the user to sources where the information was retrieved from.

However, building an effective RAG system for heritage preservation presents unique challenges. In addition to the parameters mentioned by [54], spatial relationships, temporal evolution, and the complex hierarchies of historical elements must be understood to make informed decisions. Additionally, the system must account for symmetries, orientations, and temporal changes, such as interpreting data from past conservation reports and adjusting it based on subsequent degradation or restoration efforts. Despite these challenges, employing such systems for data collection and retrieval will ensure accessibility and user-friendly interactions for a wide range of stakeholders. Furthermore, integration of this pipeline with XR platforms will support the long-term preservation of knowledge in heritage conservation.

4.4 Augmented structural inspection

Preserving the structural integrity of historic monuments is a deeply interdisciplinary task that involves the collaboration of engineers, architects, material scientists, historians, and conservators. Inspections often rely on visual observations informed by the expertise of these professionals, making the process qualitative, and often subjective. Here, AR offers significant potential to aid in the visualisation of structural analysis and support interdisciplinary collaboration. Our recent project [56] demonstrates this potential by utilising AR to inspect historic structures, with the Lausanne Cathedral as a case study.
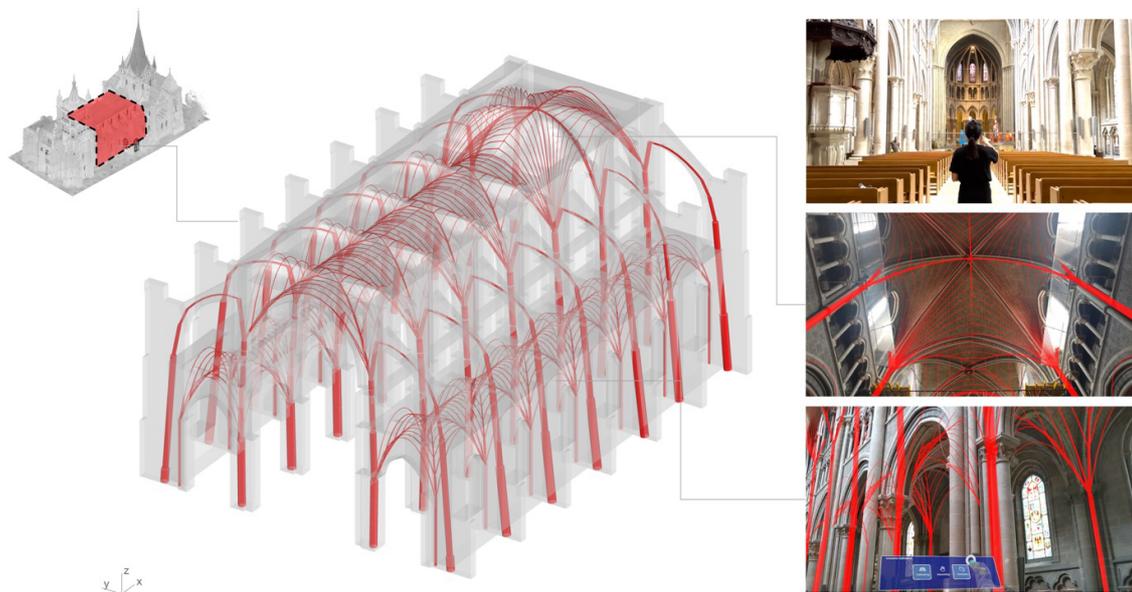

Figure 5. Left: Global structural analysis of the Cathedral showing the flow of compressive forces within the main building elements. User operating an AR platform to visualise and interact with the structural analysis results on-site.

The initiative aimed at improving the accuracy and efficiency of structural assessments of this monument by visually presenting data on its structural behaviour and highlighting vulnerabilities. This was done by integrating a digital model

with results from Thrust Network Analysis (TNA) [57], [58], [59] of the cathedral into an AR application for HoloLens 2. AR provides interactive, global visualization of the building's information and enhances collaboration by making structural

data accessible and navigable even by non-specialists. Figure 5 depicts the AR platform created projecting the digital data from the global structural analysis as overlays on the building elements in the cathedral. The underlying information about forces experienced by each element can be accessed through the native hand tracking in the device by pointing at the overlay elements [56]. This platform is particularly beneficial for inspecting hard-to-reach areas and aiding in planning interventions and maintenance activities. With the potential to expand to other monuments and disciplines, AR-based platforms represent a scalable solution for providing more accessible and tangible perspectives on structural inspections and maintenance planning across heritage buildings.

4.5   Public outreach

Successful conservation interventions often go unnoticed because their very nature involves preserving historical authenticity without altering the monument's appearance. This discretion of "a work well done" paradoxically means that the broader public, most interested in having built heritage maintained, is unaware of the financial struggles generally faced by this field. This lack of visibility, in turn, may cause reduced funding or delayed support for essential work. It is our belief that XR could be a game changer in this scenario, enhancing public engagement through its interactive capabilities. In doing so, it can reveal the importance, achievements, and needs of conservation works in a convincing manner.

Therefore, we are developing on the topic of XR-supported public outreach. In this context, we are elaborating an immersive platform for the occasion of the 750th anniversary of the Lausanne Cathedral. This project, the "Immersive Cathedral" integrates a central touch screen app and an easy-to-access XR app for smartphones and tablets. The touch screen offers a central information repertory that is easy to navigate, allowing users to explore the monument in its entirety. In contrast, the XR app provides in-depth information, making it possible to observe conservation specificities locally, such as types of damage, and timelines of stones and water management systems implemented as part of the monument's conservation strategies.

4.6   Foreseen challenges

Currently, approaches such as Heritage++ faces some challenges arising from the lack of flexibility provided by HBIM platforms. As an extension of BIM, which was developed for new design and constructions, it is still under development and faces key issues around the requirements of maintaining complex BIM-based systems, customisation, and heritage

specific data parameters. Moreover, data availability poses another substantial challenge [30]. Heritage sites are highly diverse, with unique contexts and materials, making it difficult to apply a purely data-driven or machine-learning approach. It is moreover difficult to rely on automated predictive models due to the lack of comprehensive datasets and the complexity and fragility of historical structures. Thus, heritage conservation, through these technologies must rely on hybrid approaches, combining traditional expertise with new technological solutions, while addressing data limitations and infrastructure challenges as the technologies evolve.

Spatial computing technologies, both in terms of hardware and software will be continuously evolving, so that its challenges as summarised by [26] can be expected to decrease rapidly. Apart from this, its application in heritage conservation might face additional limitations due to availability and cost of hard and software, ease of use for beginners and the development of adequate user interfaces. Despite these difficulties, investing in the development of spatial computing applications for the conservation of built heritage is essential because their potential for addressing current challenges in conservation outweighs their difficulties of adoption.

5   Conclusion

In this letter, we addressed some of the key challenges in the field of built heritage conservation and highlighted the potential of Spatial Computing technologies in mitigating them. We further explored these technologies as futuristic interfaces for visualisation and interaction with diverse datasets, providing glimpses of various initiatives being undertaken in the integrated framework of Heritage++.

An intuitive interaction with information related to built heritage can be explored in various ways. Firstly, AR promises fast and efficient data accessibility and communication for multidisciplinary on-site consultations by projecting structural, material, and weather data as interactive maps. On the other hand, VR tools provide a platform for remote consultations and collaborations, with a particular value when the monument should be examined in 3D from various angles with different fields of view than possible on site. LLM models combined with RAG pipelines show a great potential in documenting expert intuition and support it further with information retrieval. Spatial computing presents itself as the integration of all these options, with additionally the option of serving as an "at hand computer" from which data can be pulled up and visualised while inspecting a structure, rather than going back and forth between on-site and in office conditions.

Figure 6. Vision Illustration of Heritage++ as a copilot to solve various challenges in built heritage conservation.

We envision Heritage ++ as a copilot to support practitioners in identifying critical areas of degradation and visualising the damage mechanisms going backwards and forwards in time, thus enhancing the decision-making process for preservation planning. Furthermore, Heritage++ aims to serve as a collaborative platform, capturing and enhancing expert intuition to address the several wicked problems characteristic of built heritage conservation. The case studies presented illustrate how Spatial Computing, assisted with advancements in AI, can contribute to solve the diverse challenges in heritage conservation. Such a combination of technologies will enable a deeper engagement with heritage sites, transforming the way we understand and preserve our built heritage. A future where users interact with an XR assistant to seamlessly access the required information and obtain instant insights into aspects of built heritage, like materials, degradation patterns, or past interventions, lies just ahead. Continued innovation in XR, IoT, and AI will make this vision possible and increasingly accessible, making it a unique opportunity for the field of built heritage conservation to embrace.

Acknowledgements

Authorship statement (CRediT)

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