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Digitalisation and Multi-Modal Integration of NDT and Remote Sensing Data for Coastal Heritage Monitoring: The Reculver Towers and Roman Fort Demonstrator †

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Abstract

The digitalisation of Non-Destructive Testing (NDT) data is critical for the preservation of heritage assets under environmental stress. This paper presents the technical development of a digital demonstrator for the British Academy-funded project BLUE-HeArTS (BLUE Heritage through Art, Technology, and Science), which connects scientific monitoring with artistic and historic educational narratives. The study focuses on the Reculver Towers medieval church and Roman Fort site in Kent, UK, a heritage site highly vulnerable to coastal erosion. To integrate complex, multi-modal data, a three-dimensional (3D) digital model was engineered in Unity. This digitalisation process combines high-resolution 3D laser scans of the towers and surrounding topography with surface-related remote sensing datasets, including the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) maps. Additionally, the model integrates subsurface NDT data, specifically topographically corrected Ground Penetrating Radar (GPR) data, to visualise the structural integrity of sea defence areas. By digitalising these diverse datasets, ranging from electromagnetic subsurface profiles to thermal surface maps, into a single immersive environment, the system supports a holistic representation of climate-driven risks. To assess technical viability, performance was evaluated using established geospatial Extended Reality metrics. This formed the basis for frame rate profiling across different hardware configurations, including Quest 2 and 3, to measure real-time rendering efficiency. Computational efficiency was further analysed through GPU and CPU utilisation during dynamic data toggling. The performance analysis corroborates that rendering complexity remains a primary bottleneck, causing GPU overload and dropped frame rates. This study establishes a technical foundation for heritage and environment conservation digitalisation, highlighting the need for rendering optimisation.

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Keywords: digitalisation; NDT data; Ground Penetrating Radar (GPR); remote sensing; Extended Reality (XR); Unity 3D; coastal heritage monitoring

1. Background

The BLUE-HeArTS Project (BLUE Heritage through Art, Technology, and Science) framework proposes a multidisciplinary partnership between UK and European Union institutions that supports the development of a Horizon Europe Pillar 2 project proposal. The project serves as a bridge between scientific monitoring and historic preservation by synthesising technical, non-invasive scientific data with artistic and educational narratives to drive and support decision-making on vulnerable heritage sites, thereby converting scientific insights into actionable conservation strategies.

The project aims to bridge the resolution gap in open-source remote sensing by introducing a multi-scaled monitoring baseline with multi-modal data integration. This baseline provides a structured reference for coastal monitoring across three layers of increasing detail and cost: regional screening, site documentation and asset-level diagnosis. By linking scientific, cultural and stakeholder frameworks, the project translates complex remote sensing outputs into evidence for conservation decision-making. Its emphasis on open-access technologies supports implementation in resource-constrained regions and provides a scalable pathway for systematic risk prioritisation. The framework operationalises high-level global conservation and space policies into standard field methodologies, contributing, amongst others, to UN Sustainable Development Goal 11, which aims to protect and safeguard the world's cultural and natural heritage.

Overall, the BLUE-HeArTS project aims to integrate artistic creativity, advanced sensing technologies, and cultural heritage research into a unified framework to address climate–driven risks to heritage assets within the BLUE domain, that is, coastal, riverine, and subterranean water systems. This paper supports the BLUE-Hearts project by discussing the technical evaluation of a pilot demonstrator. It aims to integrate multi-modal satellite and ground-based data into an extended reality application that serves as a project demonstrator.

Study Context

Contemporary conservation of cultural heritage sites is vulnerable to critical environmental stressors. Across different geographies and climatic settings, historical monuments are constantly exposed to landscape hazards such as flooding, coastal erosion, storms, sea-level rise, and extreme temperatures, while also experiencing material decay, salt crystallisation, biological growth, thermal stress and structural damage [1,2]. These processes are not independent; environmental exposure can accelerate material decay and structural deterioration, while the condition and material properties of individual monuments influence their sensitivity to landscape hazards [3]. The combined effects of natural and coastal dynamics, land morphology, and climate-driven hazards can further complicate this interaction.

On a global scale, satellite observations show that 31% of the world's ice-free shore is made of sand, 24% of which is chronically eroding at rates exceeding 0.5 m per year. This assessment is particularly critical for protected areas, which shows that a record 37% of sandy shorelines within Marine Protected Areas are actively eroding, raising critical concerns about the survival of both ecological and cultural sites in coastal zones [4].

The Reculver Towers and Roman Fort are a prime example of coastal heritage vulnerability, situated in a highly dynamic coastal zone that is subject to geomorphic processes, such as tidal and storm surges [5]. Recorded data reflect that the site has been exposed

to continual marine erosion, storm surges and tidal fluctuations since the 12th century, which have notably consumed large sections of the original Roman fortifications. Additionally, the elevated groundwater levels in this area limit the effective drainage, reducing surface stability and affecting the performance of engineered sea defences [5]. The physical stability of the ground is not the only aspect at risk; the site's historic materials have also experienced gradual deterioration due to persistent environmental stressors active within this zone. For instance, sustained warming trends accelerate stone decay via thermal expansion–contraction cycles and moisture evaporation gradients [5].

Traditional monitoring of coastal heritage sites, such as Reculver Towers, has relied on visual inspection, periodic photographic observation, manual decay mapping and discrete environmental measurements to support conservation decisions [5]. These methods provide direct and interpretable evidence, but are often labour-intensive, spatially restricted and difficult to sustain across large or inaccessible coastal areas [6]. Current monitoring methods combine remote sensing data, Light Detection and Ranging (LiDAR), multispectral imaging, Internet of Things sensors, Ground Penetrating Radar (GPR) and structural-health monitoring to improve spatial coverage, temporal continuity and diagnostic capacity [7,8]. Nonetheless, these techniques introduce new challenges involving uncertainty, scale mismatch, registration, and interoperability. Satellite and airborne methods provide geometric and environmental information but often lack asset-level diagnostic detail, while NDT provides detailed local evidence but remains spatially limited [9,10].

Although cultural heritage has adopted many technological approaches, progress toward comprehensive sector-wide digital transformation remains uneven. The challenge extends beyond the technical to computational constraints, interoperability issues and institutional voids [11]. While these approaches have expanded the range of digital heritage documentation, they have largely developed as separate, project-specific workflows contributing to the fragmented and uneven digital transformation across the domain.

Digitisation in cultural heritage has developed through overlapping approaches rather than a single integrated system. Studies describe a growing effort to connect these outputs, while identifying challenges in interoperability, digital documentation, capturing reality, and adopting widely used end-to-end systems [7]. Baker [8] reports the use of Unmanned Aircraft Vehicles (UAVs), LiDAR and a combination of NDT and non-NDT techniques for data capture to enable the creation of point clouds, meshes, condition maps for three-dimensional (3D) models, Digital Elevation Models (DEMs), erosion assessments and archaeological insights. However, complex historic geometries, inaccessible areas, poor registration and uncertain measurements remain limitations to the data capture approach, reducing the overall reliability of the recorded datasets [7]. A central limitation to the digitisation process is that it often stops at the production of isolated digital objects such as a point cloud, a 3D model, a database, or a virtual tour. Individually, these processes may be valuable but do not automatically form continuous conservation workflows. The captured data are frequently processed separately, stored in incompatible formats or disconnected from decision-making platforms [7,11]. The main challenge is not the absence of technologies but the connection of them through shared standards, semantic models, reliable data governance, and conservation workflows [11]. To address this integration gap, the study develops and evaluates an immersive digital demonstrator for multi-modal coastal heritage monitoring.

The remainder of this paper is structured as follows: Section 2 highlights the aim and objectives, Section 3 describes the data acquisition and methodology, Section 4 presents the Extended Reality (XR) digital demonstrator, Section 5 discusses the results and limitations of the study, and Section 6 concludes with recommendations for future research and scalability.

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2. Aims and Objectives

This study aims to design and develop an immersive digital demonstrator that integrates remote sensing and NDT data within a 3D immersive environment for coastal heritage monitoring. The demonstrator is intended to support visual interpretation and contribute to informing conservation decision-making for vulnerable coastal assets. The following objectives guide the study:

1. To integrate relevant satellite remote sensing and NDT datasets within a unified immersive XR environment.
2. To measure technical performance, as well as computational bottlenecks.
3. To compare the performance of Quest 2 and Quest 3 under the same workload.

The purpose of the study is to establish the feasibility of deploying the XR demonstrator on standalone Meta Quest 2 and Quest 3 devices. The evaluation focuses on the demonstrator's ability to process, render and toggle multi-modal data, rather than assessing user experience, usability, or the effectiveness of the system.

The demonstrator integrates high-resolution 3D laser scans and satellite remote sensing datasets, specifically Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI), with topographically corrected radargrams within a single immersive platform. Furthermore, it aims to evaluate the technical viability and real-time rendering efficiency of navigating the datasets across diverse hardware configurations by profiling the frame rate stability and CPU/GPU utilisation during dynamic data toggling to pinpoint computational bottlenecks. The strategic value of multi-modal integration within the demonstrator lies in its ability to consolidate disparate, traditionally siloed data types within a single immersive environment, allowing users to visualise multiple sources of environmental and subsurface information in their spatial context. The present demonstrator is intended as a technical integration and visualisation platform rather than as a quantitative data-fusion or cross-sensor diagnostic system.

3. Methodology

This study adopted a design and development methodological approach followed by a quantitative technical evaluation. An XR demonstrator was developed by integrating multi-modal and multi-dimensional datasets into a unified 3D environment, including LiDAR-based 3D geometries, (two-dimensional) 2D GPR radargrams processed in MATLAB (R2025a), and 2D LST and NDVI maps. Technical feasibility was assessed using objective performance metrics, such as frame rate, memory saturation, and GPU and CPU utilisation.

3.1. Data Collection and Analysis Approach

Four types of data were used, two of which were collected remotely and the others onsite. The remote environmental data comprised LST derived from Landsat 8 and 9 thermal imagery and NDVI derived from Sentinel-2 multispectral imagery. Both datasets were processed within Google Earth Engine (GEE 2026), maintaining native spatial resolutions of 10 m for Sentinel-2 and 30 m for Landsat. These datasets were processed as independent environmental information layers and subsequently spatially registered for integration and visualisation within the XR demonstrator. Because no pixel-wise comparison, quantitative fusion, or statistical analysis was performed between the Sentinel-2-derived NDVI and Landsat-derived LST products, the datasets were not resampled onto a common analytical raster grid, allowing their respective spatial resolutions to be preserved.

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3.1.1. Remote Environmental Data

The LST was derived from Landsat thermal bands using the Single Channel, Mono-Window algorithm [12]. NDVI and LST products representing the 2017–2025 monitoring period were integrated to visualise vegetation condition and surface-temperature variability within the heritage site boundary. This approach is consistent with the established practices using NDVI time series to identify vegetation stress and land cover change [13], alongside LST data to assess microclimatic thermal conditions [12] and vegetation health.

3.1.2. On-Site GPR Data Acquisition and Processing

GPR data were collected through two distinct field campaigns. The first campaign used a GSSI 350 HS antenna (Geophysical Survey Systems, Inc., Nashua, NH, USA), operated through a field tablet mounted on a rugged field cart [14]. The survey covered the engineered sea defence structure installed as a conservation attempt to protect the site from further soil erosion [14]. The second campaign focused on the frame stone plaque and sections of the sea walls, surveyed using the IDS GeoRadar Aladdin system (IDS GeoRadar S.r.l., Pisa, Italy), equipped with dual-polarised 2 GHz antennas (see Figure 1).



Figure 1. GPR data collection at the sea defence walls and framed stone plaque. (**a**) Sea defence walls data capture; (**b**) data capture of stone plaque; (**c**) stone plaque; (**d**) processed GPR B-scan (top, plaque) and C-scan (bottom, sea defence wall).

The GPR data were processed using time-zero correction, dewow filtering, singular value decomposition-based background removal, non-local means filtering for random-noise attenuation, and amplitude gain compensation [15]. These procedures were applied to improve signal quality and create rendered images of the radargrams for integration with LiDAR-based geometry and other processed environmental datasets.

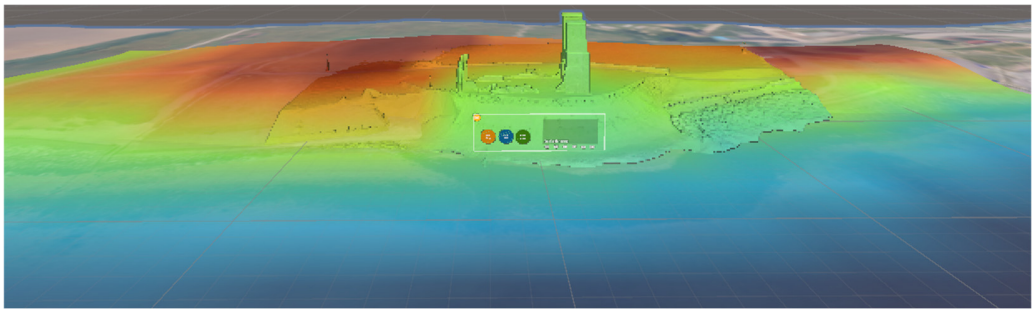
The 3D dataset combines on-site LiDAR scans with a 3D model of Reculver Towers acquired from an online 3D modelling repository. The LiDAR scans were obtained using Polycam v3.2.29 [16] to scan specific sections of the sea walls, while the repository model provided a broader structure of the twin towers. The datasets were georeferenced to assign specific coordinates and support their spatial alignment in the Unity v6.4 3D environment (Unity Technologies, 2026—a game development engine).

4. Digital Demonstrator Design and Development Approach

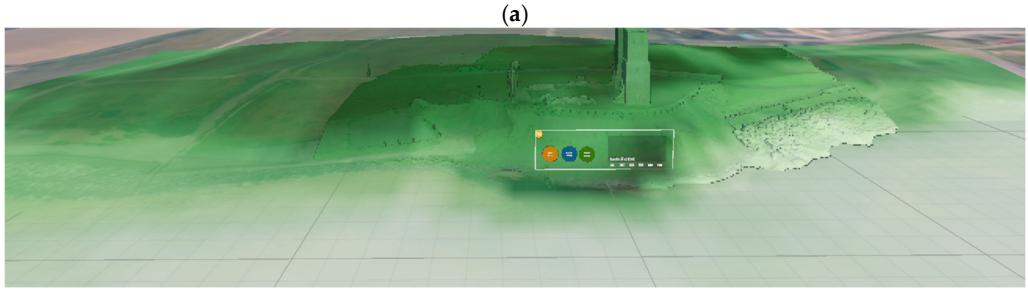
A Unity-based 3D model was developed for XR deployment. The processed LiDAR-based 3D geometry, GPR 2D radargrams, and LST and NDVI 2D maps were integrated into the model as interactive data layers. Toggle controls enabled users to interact with and concurrently visualise different data modalities, with at least two modalities displayed simultaneously. Concurrent display was intended for exploratory visual inspection within the XR environment and did not constitute quantitative comparison or fusion of the remote-sensing datasets. The demonstrator used instruction panels to introduce the application sequence and provide a general overview of the data available in the system, while intuitive buttons enabled the activation of different data modalities embedded in the 3D model. Site textures were applied to replicate the appearance of the physical site for the reconstructed model. Colour-coded graphics were used to improve the cognitive accessibility and to distinguish between remote sensing and GPR outputs, supporting data interpretation. To support the standalone XR performance, the optimisation strategy incorporated level-of-detail-based mesh reduction, Universal Render Pipeline configuration, and texture and material bandwidth management. These techniques reduced geometric rendering and memory demands while preserving the visual information.

Unity v6.4, Blender v5.1, BlenderKit v3.19, and BlenderGIS v2.2.14 supported the development process. The model was prepared and converted to a Unity-compatible format in Blender. BlenderGIS was used to align the model with its real-world coordinates, which were verified against the georeferenced survey data. The aligned model was finally exported to Unity 3D for further development (Figure 2). The processed datasets were overlaid onto the integrated 3D model and its associated 2D map using Unity's decal system. GPR data were spatially aligned with the coordinates of the survey locations, allowing the outputs to be displayed at the corresponding sections of the sea defence walls. The main development methods therefore included data format conversion, interoperability preparation, spatial registration, coordinate verification, optimisation techniques and decal-based visualisation. Technical testing assessed the demonstrator's viability on standalone Meta Quest 2 and 3. Platform-adaptive runtime profiling focused on standard XR performance test metrics such as frame rate stability, memory saturation, and CPU and GPU utilisation during the data integration, which was conducted using the Oculus Virtual Reality Metrics (OVR) Tool v2.7.

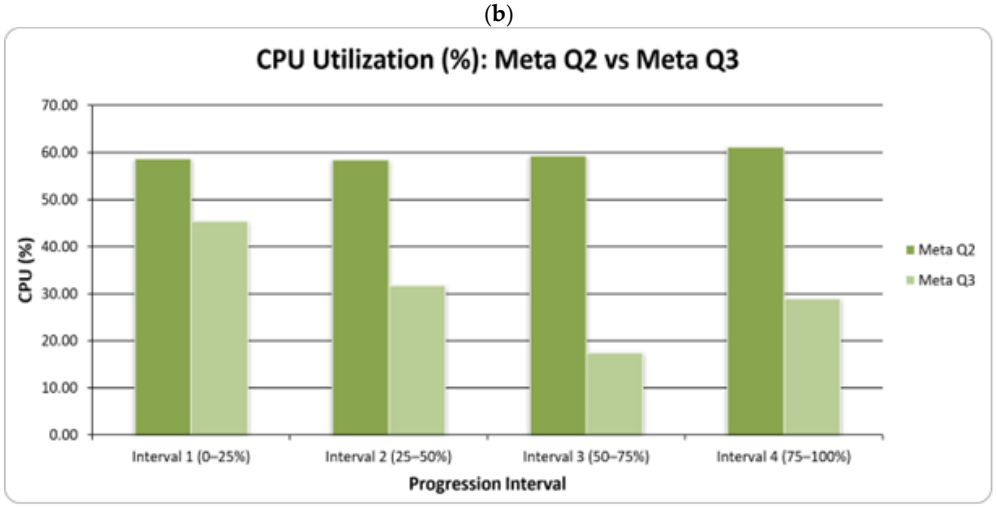
https://doi.org/10.3390/engproc2026156009



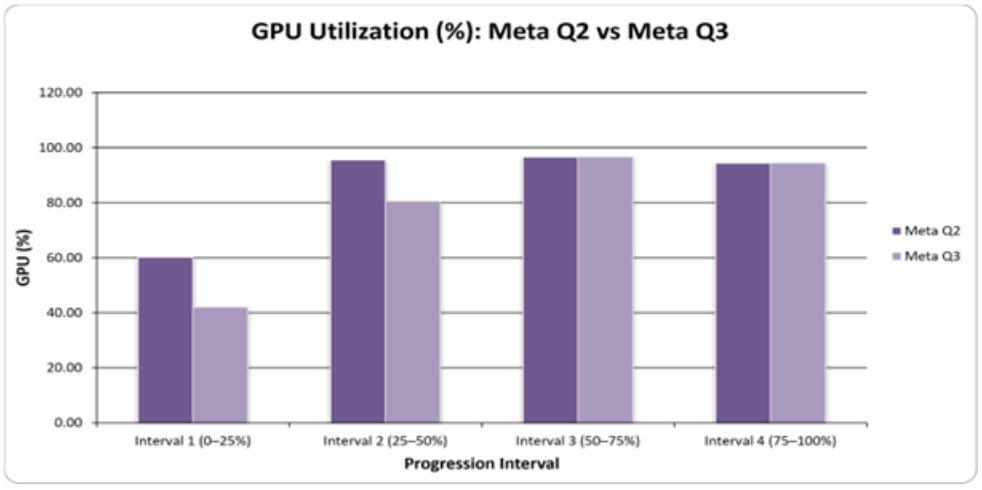
(**a**)



(**b**)



(**c**)



(**d**)

Figure 2. (**a**) Processed LST overlaid in the XR demonstrator; (**b**) processed NDVI overlaid in the XR demonstrator; (**c**) CPU utilisation comparison of Quest 2 and 3; (**d**) GPU utilisation comparison of Quest 2 and 3.

5. Results and Discussion

The results confirmed the technical feasibility of integrating heterogeneous datasets within a single immersive XR-based digital demonstrator for spatially coordinated multi-modal inspection at fixed intervals. The 72 Hz target (see Table 1) corresponds to a frame time budget of 13.89 ms, with average and minimum frames per second (FPS) and 1% low FPS used to assess frame delivery and stuttering. Conversely, CPU and GPU utilisation and bottleneck measurements were used to identify processing constraints on both Meta Quest 2 and 3.

Table 1. OVR metrics report summary for Quest 2 and Quest 3. The target refresh rate = 72 Hz.

Category	Metric	Value Quest 2	Value Quest 3
Configuration	Target Frame Time Budget	13.89 ms	13.89 ms
Frame Rate	Average FPS	42.97	63.95
Frame Rate	Median FPS	37	72
Frame Rate	Minimum FPS	19	30
Frame Rate	1% Low FPS (Stutters)	19.67	30
CPU Metrics	Average CPU Utilisation	59.41%	32.03%
CPU Metrics	95th Percentile CPU	79.65%	62.20%
CPU Metrics	Max CPU Utilisation	88.00%	79.00%
GPU Metrics	Average GPU Utilisation	86.66%	79.26%
GPU Metrics	95th Percentile GPU	97.00%	98.00%
Memory Architecture Metric	App Memory Saturation	38.72%	32.09%

The performance differed between the two tested devices, with Quest 3 delivering higher frame rates than Quest 2 under the 72 Hz target configuration. Average FPS increased from 42.9 on Quest 2 to 63.95 on Quest 3. The minimum FPS increased from 19 to 30 FPS, and the 1% low improved from 19.67 to 30 FPS. Quest 3's median reached 72 FPS, although its average remained below the target. On Quest 2, only 5.5% of recorded observations met the 72 Hz target, indicating that the target was rarely sustained, while the 1% low of 19.67 FPS indicates frequent stuttering. These results show improved frame delivery on Quest 3; however, the multi-modal rendering requires further optimisation.

Resource measurements indicated a balanced workflow on Quest 3, with average GPU utilisation decreasing from 86.66% on Quest 2 to 79.26% on Quest 3, while average CPU utilisation decreased from 59.41% to 32.03%. The profiler's bottleneck classification and high GPU and CPU utilisation on Quest 2 indicate that graphics processing remains a key constraint. Although GPU processing remained the principal constraint, the analysis showed that Quest 3 provided greater graphics headroom and a balanced workload distribution (see Table 1).

The memory metrics in Tables 2 and 3 indicate that neither Meta Quest device experienced progressive memory exhaustion during the test period. The memory was monitored as an indicator of how the demonstrator combined multiple raster layers with high resolution on the headsets with finite device resources. Memory statistics describe the application memory use and can help identify pressure associated with loading and retaining assets. They were included as contextual profiling measures, not as evidence of causing frame rate limitations. The reported memory saturation averaged 38.72% on Quest 2 and 32.09% on Quest 3. Since Meta Quest 3 used a larger physical GPU memory allocation, the Video

Random Access Memory (VRAM) physical GPU readings increased from 577.54 MB to 609 MB on Quest 2 and from 653.70MB to 695 MB on Quest 3 between the initial interval and the final interval of the test.

Table 2. VRAM physical GPU per interval for Quest 2 and Quest 3.

Metric	Interval	Value Quest 2	Value Quest 3
VRAM Physical GPU (MB)	Interval 1 (0–25%)	577.54	653.70
	Interval 1 (25–50%)	608.67	687
	Interval 3 (50–75%)	609	694.35
	Interval 4 (75–100%)	609	695

Table 3. System RAM app PSS per interval for Quest 2 and Quest 3.

Metric	Interval	Value Quest 2	Value Quest 3
System RAM App PSS (MB)	Interval 1 (0–25%)	1079.67	1174.81
	Interval 1 (25–50%)	1138.97	1238.
	Interval 3 (50–75%)	1141.24	1248.18
	Interval 4 (75–100%)	1142.81	1250

This was also observed for the system Random Access Memory (RAM) app Proportional Set Size (PSS), with an increase from 1079.67 MB to 1142.81 MB on Quest 2 and from 1174.81 MB to 1250 MB on Quest 3. These readings show an absolute memory use on Quest 3 but a lower reported saturation level relative to the profiler's indicator. It should be noted that these reported values alone should not be interpreted as proof of memory saturation or memory leakage, since this would require direct measurements of available and allocated system memory and supported graphics memory [17], with longer-duration testing.

The GPU and CPU utilisation results are consistent with [18], which reported GPU utilisation above 93% and combined modalities exhibiting frame rates between 10.5 Hz and 12.7 Hz on a standalone headset. By reporting frame rate and hardware utilisation measurements, this study extends the existing evidence base by demonstrating that the present prototype places substantial demand on both GPU and CPU resources. This contributes an additional system-level perspective towards addressing the gap identified in [19], where XR systems were commonly evaluated through task accuracy, completion time, and usability testing rather than systematic reporting of frame rate and hardware utilisation.

The findings of this study must be interpreted within the scope of this technical evaluation. The study did not encompass user-centred assessments, diagnostic accuracy testing, or decision-support evaluation. In addition, the remote sensing layers differed in spatial resolution, while the GPR data provided episodic subsurface snapshots. The datasets were rendered as independently processed, spatially registered visualisation layers without pixel-wise quantitative comparison, cross-sensor data fusion, or temporal synchronisation. Consequently, the demonstrator functions as an interactive multi-modal visualisation tool rather than an automated, cross-calibrated monitoring ecosystem.

6. Conclusions and Future Work

In this work, an Extended Reality (XR) digital demonstrator integrating multi-modal remote sensing and Non-Destructive Testing (NDT) data was implemented to support the digital transformation of traditional coastal heritage monitoring. The demonstrator was deployed on Meta Quest 2 and 3, confirming the feasibility of presenting spatially coordinated data layers on standalone headsets. Quest 3 demonstrated an increase in average frame per second (FPS) from 42.97 to 63.95 FPS, an increase in minimum frame

rate from 19 to 30 FPS, and a reported 1% low increase from 19.67 to 30 FPS. Its lower average CPU and GPU utilisation further indicates greater processing headroom under the tested workload compared to Quest 2. However, neither headset achieved the 72 Hz target display threshold across the full session, particularly after the multi-modal data overlays were introduced. The prototype implemented dynamic level of detail (LOD) hierarchies, optimised texture compression, and URP configuration. Future tests should measure registration accuracy and address the spatial and temporal differences among the remote sensing data and the Ground Penetrating Radar (GPR) data, as well as the 3D asset used. Grid-based indexing could support retrieval of multiscale layers [20,21], while temporal co-location could provide a precedent for comparing data with different spatial supports [22]. Future quantitative fusion should report its registration error and validation method.

The current evaluation was limited to technical profiling and did not assess usability, diagnostic accuracy or decision-making. Accordingly, future work should focus on fine-tuning the LOD transition distances, optimising decal overlay methods, and conducting user-centred testing to assess usability and interpretative accuracy before operationalising the XR demonstrator. To transition the system into an active monitoring framework, a dedicated data pipeline architecture is required. This architecture should facilitate temporal alignment, data interpolation, quantitative analytical comparison and the correlation of time-stamped environmental indicators with periodic asset condition assessments. Consequently, this will enable the system to support continuous monitoring, change detection and predictive deterioration modelling, rather than relying on static datasets. Finally, an optional WebXR version of the demonstrator could broaden access through supported browsers and simplify deployment updates, although it should be considered a complementary delivery route rather than a performance-enhancing solution [23]. Future work should therefore compare native and WebXR versions under identical test conditions.

Author Contributions: Conceptualization, F.T., N.L., I.C., A.L., and A.A.; methodology, D.N.D.D., S.P., M.M.N.; software, D.N.D.D., A.M.G.; validation, D.N.D.D., S.P., M.M.N., E.B., and T.T.; formal analysis, D.N.D.D., M.R., T.T., and F.T.; investigation, N.L., D.N.D.D., S.D., S.P., and M.M.N.; resources, D.N.D.D., S.P., M.M.N., O.A.O., A.M.G., and M.K.; data curation, D.N.D.D., S.P., M.M.N., O.A.O., and E.B.; writing—original draft preparation, D.N.D.D.; writing—review and editing, D.N.D.D., D.D., F.T., M.R., M.K., S.P., T.T., S.D., and I.C.; visualization, D.N.D.D.; supervision, F.T., M.R., T.T.; project administration, F.T., A.A., I.C., D.D., and A.L.; funding acquisition, F.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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