

GIS-integrated Virtual Reality/augmented Display Interactive Navigation System For Rural Cultural Heritage

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Cultural heritage visualisation and interactive exploration have been greatly improved by recent developments in Geographic Information Systems (GIS), Three-Dimensional (3D) digitisation, and immersive technologies like Virtual Reality (VR) and Augmented Reality (AR). However, managing large geographic data in real time while achieving accurate landscape representation poses a significant challenge. This paper proposes a GIS-based VR/AR interactive navigation system for rural cultural heritage sites that effectively manages large geospatial data and provides precise and immersive 3D visualizations. The proposed system utilizes preprocessed data from OpenStreetMap and QGIS to divide the data into tiles of 30 km x 30 km. A weighted ensemble machine learning (EML) architecture combining Random Forest, Gradient Boosting Regressor, and Extra Trees Regressor is used to generate precise Digital Elevation Models (DEMs), which are then converted to 3D meshes and textured. The generated 3D tiles are enhanced through layer blending and subsequently integrated into a game engine to enable an immersive VR/AR visualization experience. The system performance is also optimized by achieving higher frame rates (from 48 to 65 FPS), reduced data processing time (from 30 to 22 seconds), and increased accuracy in terrain data (from 2.2 to 1.6 meters). The experimental results demonstrate that the proposed framework provides a reliable and scalable solution for immersive rural cultural heritage visualization. This framework also offers a practical methodology for linking GIS, ML, and 3DV technologies to create immersive and engaging heritage experiences.

Keywords: Augmented reality, Digital Elevation Modelling, Ensemble Machine Learning, Geographic Information System and Virtual Reality

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1. Introduction

Augmented Reality and Virtual Reality are modern technologies that offer high-quality visualization in three-dimensional environments [1]. The latest developments in software and game engines enable these technologies to process more complex inputs, giving users a new perspective on unseen data [2]. Both AR and VR provide immersive, interactive, and engaging environments that significantly enhance user experience and spatial understanding, especially for young people [3]. The fundamental

elements of both technologies are hardware, data, and software, which have evolved rapidly to offer realistic interactive virtual environments [4]. Advanced visualization interaction capabilities of both AR and VR make them useful in learning, exploration, engagement in various domains, such as cultural heritage, gaming, and education.

Significantly, technological advancements in the field of digitization have transformed the documentation, conservation, and preservation of cultural heritage sites. Over the past two decades, aerial and terrestrial photogrammetry, terrestrial laser scanning, and UAV mapping technologies

have emerged as powerful tools for the high-resolution documentation of the entire archaeological landscape [5]. These technologies produce detailed point clouds and textured 3D models that effectively represent the structural and environmental features of the heritage site. Geographic Information Systems (GIS) have also played an important role in the management and visualization of spatial data by facilitating the integration of topographic, architectural, and environmental features into a unified platform [6].

Advanced data processing capabilities enable the integration of various scan data from different sources to build comprehensive 3D models of considerable scale [7]. Advanced postprocessing capabilities, real-time rendering, and devices with GPU capabilities, mostly driven by gaming industry needs, enable realistic visualization of complex archaeological scenes and environments [8]. Such advancements have further encouraged and promoted the use of immersive technologies such as AR and VR, extending the use of digital heritage from documentation to education, remote access, and visitor engagement [9].

- Develop a GIS-integrated VR/AR interactive navigation framework for rural cultural heritage using OpenStreetMap datasets, enabling large-scale geospatial visualization and immersive user interaction.
- Implement a tiling strategy (30 km × 30 km) combined with EML for DEM generation, followed by raster-to-mesh conversion and texture mapping for realistic 3D terrain creation.
- Integrate the generated 3D models into a game engine to support VR/AR-based interactive navigation, including features such as layer visualization, temporal analysis, and immersive exploration.

Using large Earth data, Wu et al. [10] presented a 3D GIS-based ship navigation information service system for the Arctic Northeast Passage. To promote heritage science, teaching, and conservation at the Zhoukoudian UNESCO Global Geopark, Wang et al. [11] and Dionizio et al. [12] presented a BIM-GIS integration framework for archaeological heritage documentation and promotion, demonstrating how the integration of GIS and building information modeling can support effective heritage management and visualization. Qiu et al. [13] developed an interactive, panoramic, virtual-reality system. With this technology, users acquire information about the scientific and cultural significance of heritage sites while virtually exploring them. GIS technology has also been used in a number of training sessions to analyse spatial behaviour in traditional villages and develop rural landscapes. Orlando et al. [14] used a

GIS-based territorial planning technique to examine the adaptive reuse of old agricultural structures and the alteration of rural landscapes in Bagheria, Sicily. Likewise, Wang et al. [15] and Mahesh et al. [16] used GPS-GIS tools to examine the link between spatial behaviour and exterior spatial features in ancient settlements. Finally, the significance of exact and reliable crowdsourced geospatial data in mapping and navigation was highlighted by Hosseini et al. [17], and a framework has been proposed to evaluate the performance of OpenStreetMap in navigation. Overall, the studies discussed in this section reflect the increasing use of GIS, remote sensing, and digital media in the documentation, access, and management of cultural heritage. The challenge of rural cultural heritage preservation and representation lies in the technical divide between GIS analysis and public engagement [18]. Moreover, the generation of high-resolution 3D visualizations for large regions of rural areas tends to reach the memory wall due to the computational overhead of large geospatial datasets in traditional VR/AR platforms.

Table 1 shows the proposed GIS-EML-VR/AR framework, which integrates advanced GIS, EML, DEM modeling, VR, AR, interactive navigation, and comparisons with existing approaches. The proposed GIS-integrated VR/AR framework combines GIS preprocessing, Ensemble Machine Learning-based DEM generation, raster-to-mesh transformation, texture mapping, and game engine integration to support scalable processing, accurate terrain representation, and immersive navigation.

2. Materials and methods

A GIS-integrated VR and AR interactive navigation system is presented, ensuring real-time performance, terrain representation, user engagement and scalable geographic data handling.

Fig. 1 illustrates the overall workflow, from OpenStreetMap acquisition and QGIS preprocessing through 30 km × 30 km EML-based DEM generation and immersive VR/AR visualization.

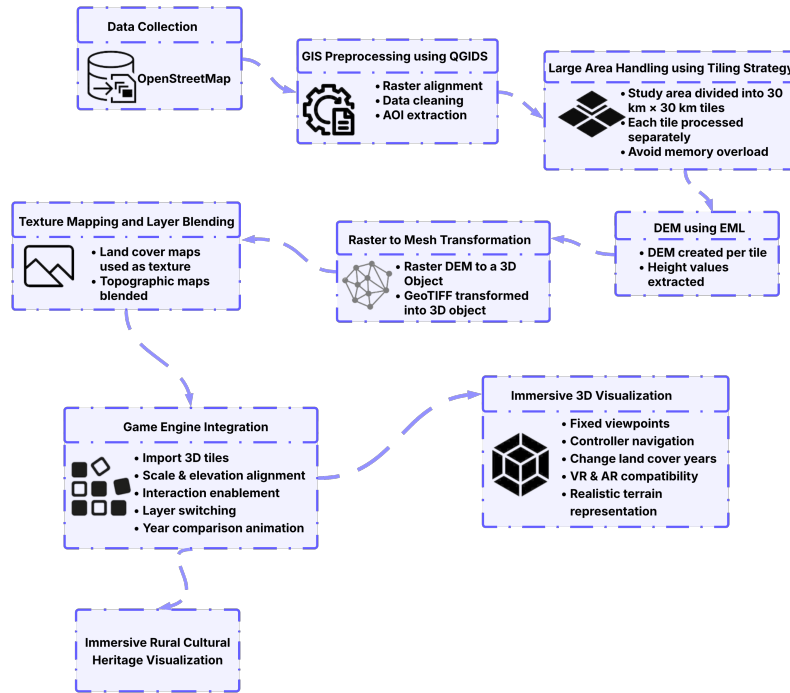
The integrated workflow connects OpenStreetMap acquisition and QGIS preprocessing with 30 km × 30 km tiling, EML-based DEM generation, raster-to-mesh conversion, texture mapping, blending, game-engine integration, and immersive VR/AR spatial visualization.

The strategy improves computational overhead, improves memory efficiency, and enables scalable immersive visualization, as demonstrated in Eq. (1).

$$A = L_x \times L_y \quad (1)$$

Table 1. Comparison of Recent GIS-Oriented Cultural Heritage Visualization Frameworks

Approach	Advanced GIS	DL / ML	Photogrammetry	DEM / Terrain Modeling	VR	AR	Interactive Navigation
3D GIS + Big Earth Data [10]	✓	-	-	✓	-	-	Partial
3D GIS + Neural Network [11]	✓	✓	-	✓	Partial	-	Partial
BIM-GIS Heritage Framework [12]	✓	-	Partial	Partial	Partial	-	Partial
Panoramic VR Heritage System [13]	Partial	-	Partial	-	✓	-	✓
AR Cultural Preservation Framework [16]	Partial	✓	-	-	-	✓	✓
Proposed GIS-EML-VR/AR Framework	✓	✓ EML	-	✓	✓	✓	✓

**Fig. 1.** Proposed GIS-based workflow for immersive VRAR terrain visualization

Here, A represent the total spatial area, L_x and L_y represent the total spatial extent in the x and y directions. Memory requirement per tile is given in Eq. (2).

$$A' = \cup_{i,j} T_{ij} \quad (2)$$

Here, $\cup_{i,j}$ is the processed tile at position, T_{ij} is the processed tile and A' is the final reconstructed data.

Fig. 2 shows the scalable tiling-based parallel processing

approach, dividing DEMs into overlapping tiles for efficient processing, mesh generation, and VR/AR navigation. The adopted 30 km × 30 km tiling strategy was selected to balance spatial coverage and computational requirements for large-scale geospatial processing. This arrangement limits the amount of data handled simultaneously, reducing memory requirements and computational load while enabling parallel DEM generation, raster-to-mesh conver-

sion, and texture mapping. It also supports continuous terrain reconstruction through tile integration, elevation alignment, and selective tile loading for efficient real-time VR/AR navigation. Each element in $Y_i \in \mathbb{R}^{m \times n}$ represents the height value at position (x, y) . The objective is to learn a mapping function f_θ such that the relationship between the input variables and the target output is defined as given in Eq. (3).

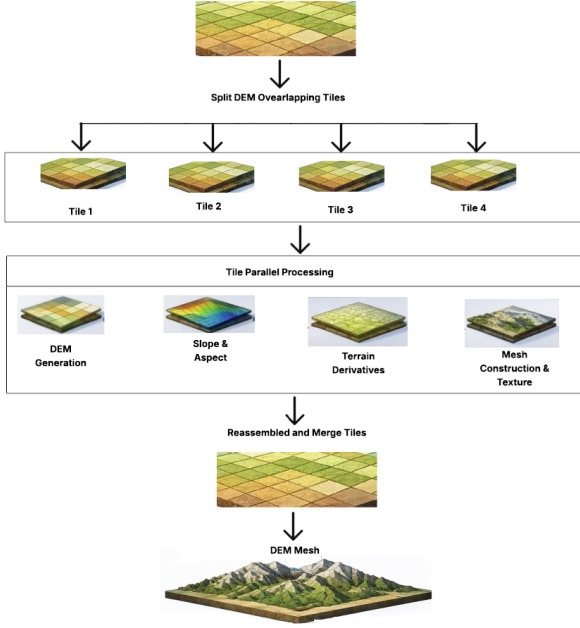


Fig. 2. Parallel tiling architecture for efficient high-resolution DEM generation.

$$\hat{H}(x, y) = \sum_{k=1}^K w_k \cdot H_k(x, y) \quad (3)$$

In $\hat{H}(x, y)$ represents the predicted elevation at location (x, y) , $H_k(x, y)$ represents the prediction from k^{th} machine learning model, w_k represents the weight assigned to the model k and K represents the total number of models. This ensured the relative importance of each component was maintained while avoiding any mismatch in the predicted elevation values in Eq. (4).

$$\sum_{k=1}^K w_k = 1 \quad (4)$$

In this equation, w_k weight assigned to model k and K total number of models. For each raster cell in all tiles, forecasted height was extracted and retained as vertical data, as given in Eq. (5)

$$M_{esth_{ij}} = f(Z_{ij}) \quad (5)$$

Where, Z_{ij} is extracted elevation values, Mesh $_{ij}$ generated a 3D terrain mesh f raster-to-mesh transformation function. The EML model utilizes raster elevation values, spatial coordinates, slope, aspect and neighbouring elevation information extracted from each $30 \text{ km} \times 30 \text{ km}$ tile as input features for DEM generation. Before prediction, all raster datasets are aligned, clipped, cleaned, normalized and interpolated, with RMSE DEM Error validating elevation accuracy.

Algorithm 1: EML Algorithm for DEM Generation

Input:

Ground truth elevation samples G

Output:

Ensemble-based Digital Elevation Model (DEM_EML)

Begin

1 Data Integration

$D_{\text{clean}} \leftarrow$ Remove noise and missing values from D

$D_{\text{align}} \leftarrow$ Align spatial resolution and coordinate system

$D_{\text{norm}} \leftarrow$ Normalize elevation values

2 Feature Construction

For each spatial location (x, y) :

Extract features $F(x, y)$ from D_{norm}

End For

3 Generate Predictions

For each spatial location (x, y) :

$P1 \leftarrow$ Predict (Model 1, $F(x, y)$)

$P2 \leftarrow$ Predict (Model 2, $F(x, y)$)

$P3 \leftarrow$ Predict (Model 3, $F(x, y)$)

End For

4 Ensemble Aggregation

For each spatial location (x, y) :

$$DEM_{EML}(x, y) \leftarrow w_1 \times p_1 + w_2 \times p_2 + w_3 \times p_3$$

End For

$$/ / \text{ where } w_1 + w_2 + w_3 = 1$$

5 DEM Reconstruction

Interpolate DEM_EML to continuous raster surface

6 Output

Export DEM_EML as final Digital Elevation Model

End

Algorithm 1 shows that the EML algorithm proposed herein generates an accurate DEM by integrating the outputs of multiple models. The interpolated DEM surface is constructed by estimating continuous elevation values from the ensemble-predicted raster cells while preserving spatial continuity between neighbouring locations. This interpolation process minimizes abrupt elevation transitions, generating a continuous DEM with complete terrain representation for 3D VR/AR visualization. The proposed EML model employs a weighted ensemble of Random Forest, Gradient Boosting and Extra Trees regressors using spatial coordinates, slope, aspect, neighbouring elevation values as input features. Validation-based hyperparameter optimization (50-200 trees, maximum depth 5-20) with a 70%/15%/15% data split was adopted. Normalised ensemble predictions were then interpolated to generate the final DEM.

Normally, a grid cell is divided into two triangles. This creates a continuous 3D surface that represents the terrain in Eq. (6)

$$F = \left\{ \left(V_{i,j}, V_{i+1,j}, V_{i,j+1} \right), \left(V_{i+1,j}, V_{i+1,j+1}, V_{i,j+1} \right) \right\} \quad (6)$$

Here, F represents triangular faces and $V_{i,j}$ is vertices at grid position (i, j) . For every 30 km $\times$ 30 km tile, a full 3D mesh object was generated.

Fig. 3 shows the architecture for converting raster elevation data into 3D mesh models through (x, y, z) vertices, connectivity, triangulation, faces and normals. The blending coefficient controls the degree to which the features of the terrain are emphasised in Eq. (7)

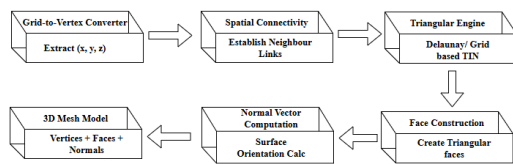


Fig. 3. Architecture of Raster-to-Mesh Transformation for 3D Terrain Modeling.

$$C_{\text{blend}}(x, y) = \alpha \cdot C_{\text{tex}}(x, y) + (1 - \alpha) \cdot \text{Topo}(x, y) \quad (7)$$

Here, $C_{\text{blend}}(x, y)$ represents the final blended colour, α represents the blending coefficient, C_{tex} represents the base

texture colour, and $\text{Topo}(x, y)$ represents the topographic map value. The blending coefficient α ranges from 0 to 1 ($0 \leq \alpha \leq 1$).

An illustration of the process for texture mapping and blending layers is shown in Fig. 4, integrating DEM terrain, satellite imagery, land cover, slope, and aspect maps for realistic VR/AR visualization. The game-engine rendering pipeline used real-time forward rendering with EML-generated DEM terrain meshes, mesh simplification, LOD management, texture compression, mipmapping, resolution scaling, directional lighting, distance-based shadows, terrain collision, and on-demand asset loading for efficient VR/AR navigation.

GPU-accelerated rendering executes terrain mesh rendering, texture mapping, and lighting operations, while the 30 km $\times$ 30 km tiling strategy enables parallel tile processing with balanced workload distribution to reduce memory usage and rendering latency. Multithreaded execution separates tile loading, while LOD optimization maintains smooth VR/AR navigation, rendering time, and FPS performance. To gather geospatial data for this study, the OpenStreetMap (OSM) planet-wide dataset snapshot (November 2019) [19] was used, providing a clearly defined temporal reference for GIS preprocessing and subsequent VR/AR framework development.

The GIS preprocessing was performed sequentially in QGIS by applying raster reprojection, raster alignment using bilinear resampling, AOI clipping, raster normalization, data cleaning, and quality assessment before generating 30 km $\times$ 30 km tiles. The software parameters, including the common CRS, bilinear resampling method, and GeoTIFF output format, were applied during preprocessing for reproducible and consistent execution. OpenStreetMap data were obtained through Geofabrik and processed in QGIS by performing raster alignment, data cleaning, AOI extraction, clipping and harmonization before generating 30 km $\times$ 30 km tiles. Satellite imagery and topographic maps were used with preprocessed GIS data to generate DEM and 3D terrain models. Hardware and software configuration includes Intel Core i9-14900K, 32 GB RAM, 64-bit architecture, and Windows 11 Home 25H2 for GIS-integrated VR/AR. The game engine used for 3D terrain rendering and VR/AR interactive navigation was Unity 2022.3 LTS, ensuring reproducibility of the visualization environment and implementation. The hyperparameter configuration uses 30 km $\times$ 30 km tiles, 50-200 trees, 256-512 pixel meshes, 512-2048 pixel textures, 2-5 LOD levels, 30-60 FPS, <20 ms latency, and 72-120 Hz refresh. The EML protocol independently trained Random Forest, Gradient Boosting Regressor, and Extra Trees Regressor using the same train-

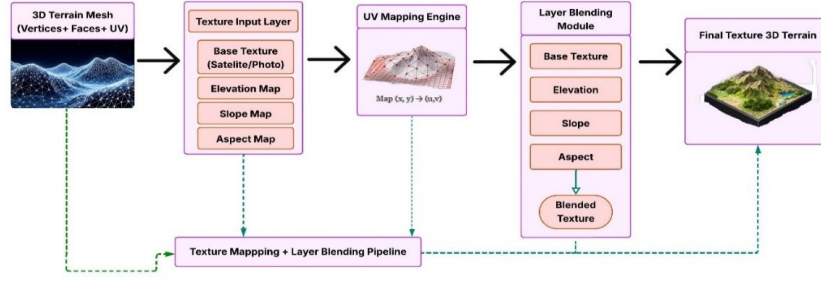


Fig. 4. Architecture of Texture Mapping and Layer Blending for 3D Terrain Visualization.

ing feature set and elevation targets with a 70%/15%/15% training, validation, test split. RF used 150 trees with a depth of 15, GBR used 120 estimators with a learning rate of 0.05 and a depth of 5, while ETR used 150 trees with a depth of 15. Equal initial weights were optimized by validation RMSE, yielding RF = 0.40, GBR = 0.35, ETR = 0.25, improving DEM robustness.

RMSE: Measures the average deviation of terrain elevation in the DEM or mesh from ground truth. The lower the value, the more accurate the terrain representation. The RMSE is given in Eq. (8)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (z_i - \hat{z}_i)^2} \quad (8)$$

Where, n is the total number of points, z_i is the true elevation of the point i and $\hat{z}_i$ is the predicted elevation from DEM or mesh.

3. Results and discussion

The main objective of conducting this research is to develop a GIS-integrated VR/AR system, evaluating rendering time, FPS, RMSE, processing time, and DEM error. User interaction evaluation involved 30 participants comprising GIS/geospatial experts, cultural heritage professionals, experienced VR/AR users, and general users. Descriptive statistical analysis based on the usability evaluation gave mean scores of 4.46/5, 4.41/5, 4.53/5, 4.38/5, 4.47/5, 4.35/5, 4.44/5, with task completion 93.30%, navigation success 96.70%, SUS 86.2/100. Element-wise performance evaluation indicates that GIS pre-processing completed in 3.8 s with 98.2% alignment accuracy, while EML-based DEM generation required 5.6 s and achieved an RMSE of 1.6 m. Raster-to-mesh conversion (3.4 s, 97.6%), texture mapping (2.7 s, 96.9%), blending (2.1 s, 97.3%), integration (2.4 s, 65 FPS), and navigation (15.4 ms) collectively demonstrated efficient real-time VR/AR performance.

Computational performance analysis covered CPU usage (38.6%, 52.4%, 67.8%), GPU usage (34.2%, 49.7%, 64.5%

), memory usage (2.8, 4.6, 7.9 GB), stage complexity ($O(N) - O(M \cdot T \cdot N \log N)$), scaling complexity ($O(kN)$), execution cost (1.2-8.6 s), peak memory usage (0.31-1.35 GB), rendering time (2.2 ms), frame rate (65 FPS), navigation latency (15.4 ms), processing time (22 s), RMSE (1.6 m), and DEM error (1.4 m). These results demonstrated practical significance through efficient computation, scalable processing, accurate terrain modeling, smooth rendering, and responsive real-time VR/AR navigation, with DEM prediction and 3D rendering identified as the main processing bottlenecks.

The study area includes four representative regions across China: Jiangwan, Xiaoqi, Huangling and Likeng, covering various types of terrain features like cities, mountains, and rural areas.

Fig. 5 presents the 3D terrain visualization results for four study areas: Jiangwan, Xiaoqi, Huangling, and Likeng, using high-resolution DEMs and texture blending.

Fig. 6 shows the graph of FPS performance for four processed tiles, rising from 48, 55, 60 to 65 FPS, indicating improved rendering performance.

The RMSE fluctuation across four tiles is depicted in Fig. 7, decreasing from 2.2 m, 2.0 m, 1.8 m, to 1.6 m, indicating improved accuracy.

The four tiles' differences in processing time are shown in Fig. 8, decreasing from 30s, 27s, 25s to 22s, indicating improved computational efficiency. Fig. 9 depicts DEM predictions closely following the 1:1 line, demonstrating highly accurate terrain modelling with minimal errors.

The ablation study of various models is summarized in Table 2. The baseline model achieved a lower FPS, whereas the proposed model achieved 65 FPS, an RMSE of 1.6 m, and a DEM error of 1.4 m.

Table 3 compares existing methods, where the proposed GIS-EML-VR/AR achieves 2.2 ms rendering time, 65 FPS, 1.6 m RMSE, 1.4 m DEM error, and 22 s processing time.

Table 4 reports GIS-EML-VR/AR achieving 65 FPS, 15.4 ms latency, 22 s processing time, high scalability, and com-



Fig. 5. Generated 3D terrain visualizations across representative study areas (a) mountainous region, (b) semi-urban area, (c) complex terrain with road networks, and (d) rural valley landscape.

Table 2. Ablation Study of Model Performance

Model	Rendering time (s)	FPS (frames/s)	RMSE (m)	Data processing time (s)	DEM error (m)
Baseline	1.2	48	2.1	30	2.1
Baseline+ Tiling	2.5	55	2.0	27	1.9
Tiling + EML-based DEM	1.6	60	1.8	25	1.7
Proposed	2.2	65	1.6	22	1.4

Table 3. Quantitative Comparison with Existing Methods

Method / Framework	Rendering Time (ms)	FP S	RMSE (m)	DEM Error (m)	Data Processing Time (s)
Conventional GIS-based Visualization	4.6	42	2.7	2.9	34
3D GIS + Big Earth Data [10]	3.5	50	2.1	2.5	28
3D GIS + Neural Network [11]	2.8	57	1.9	2.0	26
BIM-GIS Heritage Visualization [12]	3.9	47	2.4	2.6	31
VR-based Heritage Visualization[13]	3.2	54	2.2	2.3	27
GIS-based Rural Landscape Method [14]	3.7	49	2.3	2.4	29
AR-based Cultural Heritage Framework [16]	3.0	56	2.0	2.2	26
Proposed GIS-EML-VR/AR	2.2	65	1.6	1.4	22

bined VR+AR support, outperforming cited methods.

Table 5 shows rendering times of 1.6-3.1 ms and FPS of 78-57 across increasing scene complexity, terrain density, object counts, and visualization scales.

Table 6 presents validation results across diverse rural heritage environments, achieving 65 FPS, 1.60 m RMSE,

1.40 m DEM error, and 22.0 s processing time.

4. Conclusion

The results of this work demonstrate the effectiveness of the proposed GIS-integrated VR/AR interactive navigation system in improving immersive visualization and explo-

Table 4. Comparative Benchmarking of GIS-Oriented VR/AR Navigation Approaches

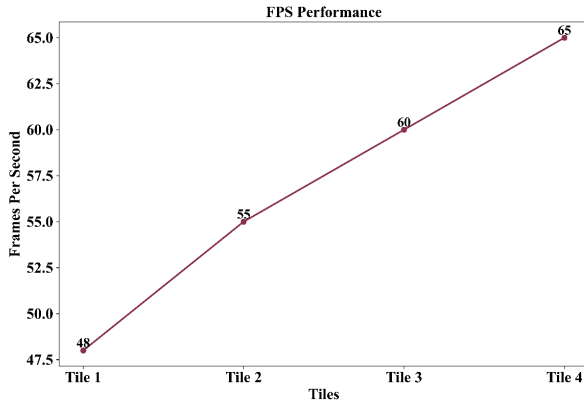
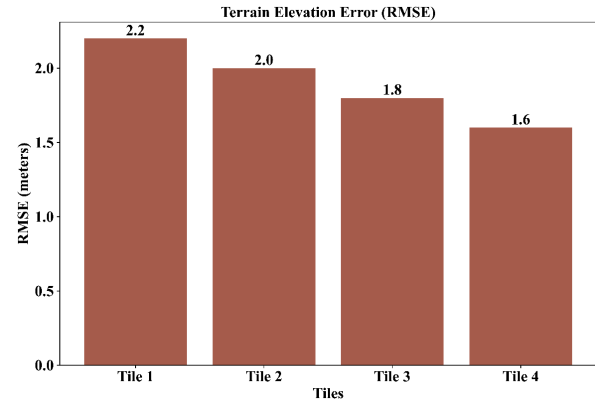
Method	FPS	Navigation Latency (ms)	Processing Time (s)	Scalability	VR/AR Support
Traditional 3D GIS	45	24.8	32	Low	Limited
3D GIS + Big Earth Data[10]	50	21.6	28	Moderate	Limited
3D GIS + Neural Network [11]	57	18.9	26	Moderate	Partial
BIM-GIS Heritage Framework [12]	52	20.3	29	Moderate	Partial
Conventional GIS-VR	55	18.1	27	Moderate	VR
GIS-AR Navigation	58	17.2	25	Moderate	AR
Proposed GIS-EMLVR/AR	65	15.4	22	High	VR + AR

Table 5. Rendering Performance across Different Visualization Conditions

Scene Complexity	Terrain Density	Object Count	Visualization Scale	Rendering Time (ms)	FPS
Very Low	Sparse	500	5 × 5 km	1.6	78
Low	Low	1,000	10 × 10 km	1.8	73
Medium	Moderate	2,500	20 × 20 km	2.0	69
Standard	Medium-High	5,000	30 × 30 km	2.2	65
High	Dense	7,500	40 × 40 km	2.6	61
Very High	Very Dense	10,000	50 × 50 km	3.1	57

Table 6. Validation Across Diverse Rural Cultural Heritage Environments

Test Scenario	Terrain / Land Cover	OSM	FPS	RMSE (m)	DEM Error (m)	Time (s)
Rural Heritage Village	Low / Agricultural	Dense	67	1.48	1.31	19.6
Mountain Heritage Area	High / Mountain	Moderate	61	1.78	1.59	25.8
Riverside Landscape	Medium / Water	Moderate	64	1.63	1.43	22.9
Forest Heritage Region	High / Forest	Sparse	60	1.82	1.64	26.4
Agricultural Landscape	Low-Medium / Cropland	Dense	66	1.54	1.35	20.7
Mixed Rural Region	Medium-High / Mixed	Mixed	63	1.69	1.50	24.1
Overall	Mixed / Multiple	Multiple	65	1.60	1.40	22.0

**Fig. 6.** FPS comparison demonstrating smooth real-time visualization.**Fig. 7.** RMSE comparison demonstrating improved terrain prediction accuracy.

ration of rural cultural heritage environments. This study presented a GIS-integrated VR/augmented display interactive navigation system for rural cultural heritage to enhance the visualization of largescale geospatial data. In the proposed framework, the tiling strategy, EML DEM

generation, and texture mapping are integrated to enhance the performance of the system. The experimental results show the superior performance of the proposed system by achieving 65 FPS, reduced time for rendering (2.2 ms), reduced time for data processing (22 s), and accuracy of

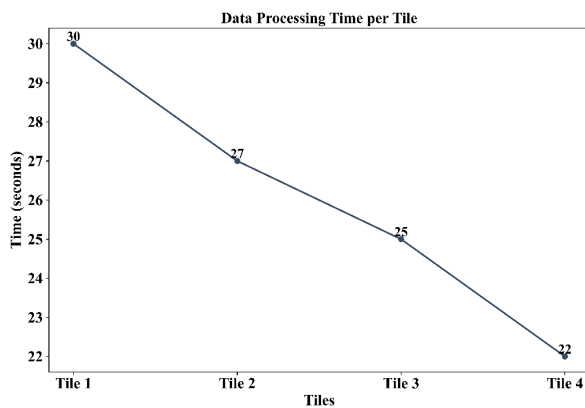


Fig. 8. Processing time comparison demonstrating efficient GIS data handling.

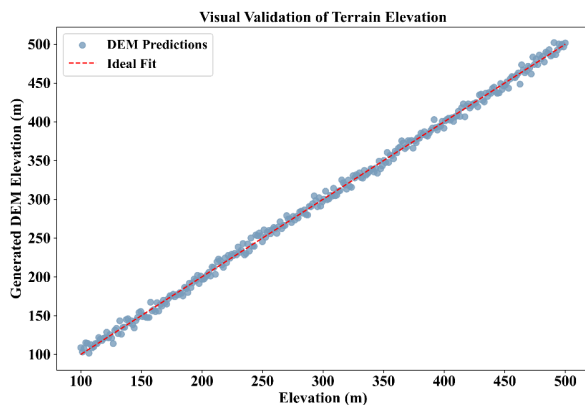


Fig. 9. Predicted and reference DEM comparison validating model accuracy.

the proposed system by achieving 1.6 m for RMSE and 1.4 m for DEM error. The results show the superiority of the proposed system over the existing systems. Overall, the framework offers a scalable, accurate, and robust solution for immersive rural cultural heritage applications. Future work can include integrating real-time sensor data and IoT for dynamic environment updates, integrating more advanced deep learning models for further improvement of DEM accuracy, and expanding the framework for support of multi-user collaborative VR/AR environments for interactive exploration of cultural heritage.

5. Acknowledgement

Declarations

Data availability

The data used to support the findings of this study are available from the corresponding author upon reasonable

request.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Author contributions

Conceptualization, methodology, software development, data collection, formal analysis, visualization, writing-original draft preparation, and writing-review and editing were performed by the author(s). All authors have read and approved the final manuscript.

Ethical approval

This study did not involve human participants, animals, or any personal data requiring ethical approval. Therefore, ethical approval was not required.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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