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Ancient Culture Exhibition Integrating Mobile Network and Virtual Reality: Immersive Experience of Historical Sites Based on Geographic Information System

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SUMMARY: *This research puts emphasis on solving problems in digital heritage showing systems, including broken space information expression, complicated 3D scene arrangement, high mobile equipment processing requirements, and restricted cultural content depth. Taking one already finished immersive ancient cultural exhibition project as case research, we on system summarize system design ideas, development procedures, core technology realizations, and application results. By making use of Geographic Information Systems (GIS) which serves as spatial data infrastructure, this project has built an immersive heritage display platform that is compatible with mobile networks. It has realized the unified gathering of multi-source different-kind site data, coordinate registering, semantic marking, spatial database building, and virtual reality scene arrangement, hence forming an overall technical framework that includes data layers, service layers, application layers, and interaction layers. In the development process, important key stages contain: establishment of basic geographic information data bank for heritage places, high-accuracy three-dimensional rebuilding of core building constructions, making of historical renovation models, drawing of spatial index maps, lightening mobile VR picture rendering, multi-equipment adaptation, and multi-people cooperative interaction functions. Test outcomes prove that mean first-screen loading periods under Wi-Fi and 5G networks are still lower than 2.8 seconds and 3.4 seconds separately, hence key area scene changes are finished inside 1.6 seconds. Mobile devices can keep stable frame numbers which are above 42 fps, therefore VR terminals constantly get frame rates that exceed 58 fps. The user satisfaction metrics which include immersion quality, content comprehension and operational convenience have achieved 91.3 percent. The research results prove that this system has strong space expression abilities, working stability, and culture spreading effect, hence it hence provides a reusable technology frame for digital display projects of historical sites.*

KEYWORDS: *mobile network; virtual reality; geographic information system; historical sites; system development; immersive display*

1 Introduction

Digital manifestation of historical places has already become a very important constituent part in cultural heritage protection, public propagation, and intelligent tourism development.

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Along with the ceaseless progressions in 3D rebuilding, space information services, and immersion interactive technologies, the construction objectives for ancient culture exhibition platforms are moving toward overall merging of scene rebuilding, space cognition, knowledge connection, and multi-equipment spreading[1]. Traditional show methods mainly depend on character descriptions, entity sand tables, and still boards, which are fit for basic knowledge passing and partial information adding but have obvious restrictions in spatial structure showing, historical background rebuilding, and user participation depth. Historical relic places themselves by nature hold features including big space ranges, shape decaying, complicated information rank structures, and long time changing processes, therefore it brings difficulty to single display media for completely passing their culture meanings and space logics[2]. This project puts emphasis on finishing digital reconstructions of real historical places and working out mobile network virtualization schemes, the core tasks contain unified space coordinate frameworks, high-quality historical scene rebuilding, stable resource delivery under mobile networks, and immersive interaction experiences through virtual reality equipment[3]. For a regionally representable ancient relic location, this item includes four resource kinds: present site situations, historical rebuildings, archaeology materials, and culture explanations. The goal is to put together elementary geographic message, place entity materials, three-dimensional modeling resources, and cultural explanations into a continuable immersive exhibition system that runs under unified space coordinate frameworks and standardized thing coding systems[4].

2 Literature Review

The investigation regarding digital displaying of historic relic spots has already passed three developing phases: it transforms from two-dimensional information digitalization to three-dimensional visual expression, and finally completes the establishment of immersion-type interaction platforms. The early-stage achievements mainly concentrated on the digitization of cultural relic files, the exhibition of two-dimensional drawings and the realization of basic information searching systems, whose goal is promoting the promotion efficiency and searching ability of cultural heritage files[5]. Along with the wide use of photogrammetry, laser scanning, 3D modeling, and GIS technologies, research key points have moved toward rebuilding place space structures, expressing district environments, and combining multi-media explanation systems[6]. This technical progress has given historical place displays with much strengthened space visual expression abilities[7].

The function of GIS technique in cultural heritage digitized work has already got large-scale verification. Research has the conclusion that GIS systems supply a unified space reference frame and strong geography information management abilities, hence hence proving especially effective for history site boundary management, environment relation expression, archaeology site arrangement, and space-time change show[8]. The progress of 3D GIS has helped the combined expression of space objects and property data, thus expanding historical site displays from plane map viewing to multi-level space knowledge understanding. At the same time, the usage of virtual reality in the spreading of ancient culture has greatly promoted user's immersive experience and interactive participation, hence related implementations are at present widely used by digital museums, archaeological park guiding systems, and educational exhibition platforms[9].

Nowadays research has built comparatively complete method systems on the single technology layer, but the combined carrying out on the engineering project layer still meets a number of usual difficulties. First of all, to realize the spatial consistency, semantic matching, and resource unification among multi-source different-type archaeological relic data still has technical difficulties, therefore this influences the platform development efficiency and display consistency. Secondly, GIS platforms as well as VR environments are frequently developed on independent systems, hence this leads to insufficient coordination between spatial information management and immersive application programs[10]. Thirdly, the visualization of historical places in mobile network environments has high sensitivity to terminal calculation ability, network delay, and resource distribution mechanisms, with the operation stability in complex scenes still being the main technical difficulty for engineering application. The present article investigates the organization methods and realization results of related technologies by the perspective of finished project systems[11].

3 System Overall Architecture and Data Planning

In the development stage, this project has built a complete system structure which is made to fit archaeological site show demands, and it combines spatial data handling, 3D resource arrangement, work logic control, and immersion interaction into one whole platform framework[12]. This system uses a GIS platform to be its core supporting layer, it connects upwards to 3D resource management modules, VR display modules, and multi-terminal access modules, hence it connects downwards to multi-source data processing work flows and spatial data bases. The entirety of the architecture has already obtained complete realization in the period of the project's deployment, and it has already passed through many rounds of work of debugging and testing.

Table 1: Overall System Module Composition and Functional Division of Labor

Module Level	submodular	major function	Deployment location
data access layer	Aerial survey access, point cloud access, literature access, multimedia access	Import of raw data and preliminary validation	Data processing server
Data processing layer	Coordinate registration, model cleaning, semantic annotation, resource coding	Standardized processing and unified organization	Data processing server
space service layer	GIS services, spatial queries, path analysis, layer management	Geographic Information Release and Indexing Positioning	Cloud server
Application Support Layer	Resource scheduling, scenario control, log recording, and collaborative synchronization	Running Logic and State Management	Cloud server/edge node
Terminal Presentation Layer	Mobile, VR, and Teaching	Display, Interaction, Roaming, and Collaborative Experience	subscriber terminal

3.1 System Architecture Design in Mobile Network Environments

This system uses a deployment structure which combines cloud services, edge caching and terminal rendering together. The back end service module which is arranged on cloud servers undertakes spatial data service issuing, resource index management, user request handling, back end management and working, and cooperative condition keeping. Edge nodes store resources for high-frequency use situations and hot topic interpretations to reduce the influence of mobile network changes on end device access. Front-end application programs which operate on mobile and VR equipment undertake the work of scene visual display, interactive reaction, partial cache taking out, and user operation feedback.

The development frame of the project divides the system into five function layers. The first level acts as the data input layer, it is responsible for receiving terrain measuring data, inclined photographing outcomes, point cloud data, written document materials, and multi-media resources. The second level serves as the data handling stratum, it carries out coordinate unification, form transformation, model purification, target coding, and attribute arrangement. The third level makes up the spatial service layer, it provides core services which are based on GIS platform, these include base maps, thematic layers, spatial queries, position obtaining, and route analysis. The fourth level plays the role of application support layer, it is responsible for managing scene change, resource distribution, interactive trigger methods, interaction logic management, and user state synchronization. The fifth layer offers the final display level, which provides functions that fit special devices, including guided direction guidance, immersive walking around, knowledge showings, and joint multi-user experiences.

In the process of system running, the GIS platform acts as the core part which is in charge of spatial object index building and scene position confirming. Every object from archaeological site is given a sole distinguishing number in the data bank, which establishes mapping connections between it and model resources, written descriptions, sound guide materials, and mutual action scripts. When users enter a particular region through terminal equipment, the system firstly obtains the space coordinates and resource indexes of related objects from GIS services, before it shows the real content. This design comparatively greatly promotes resource obtaining uniformity and system upkeep efficiency in the process of development stages.

Under the environments of mobile network, the organization of resources adopts a hierarchical loading strategy. When the system begins to start, the priority is given to the loading of basic terrain data, regional boundary lines, path information, and simplified models in order to satisfy the needs of navigation and overall survey. When users go into key regions, the system keeps on loading high-accuracy models, local surface textures, voice explanations, and repair moving pictures. The resources of hotspot regions are pre-stored at edge nodes, and terminals obtain them when needed according to access priority order.

Table 2: System loading performance test results under different network environments

Network Type	First Screen Load Time/s	Key Area Incremental Load/s	Packet Loss Rate/%	Interaction Response/s
Wi-Fi	2.8	1.3	0.4	0.42
5G	3.4	1.6	0.7	0.48
4G	5.1	2.4	1.9	0.73

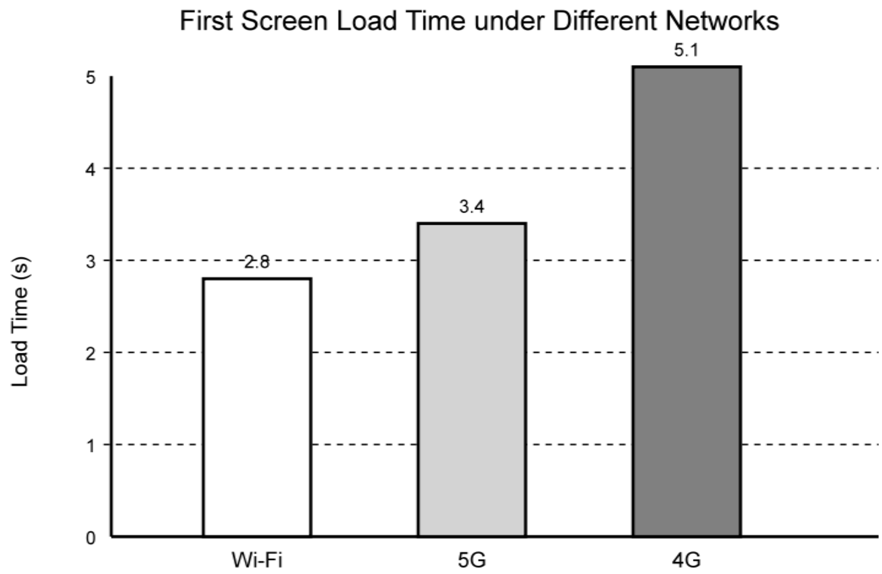

Figure 1: Comparison of first-screen loading time under different network environments

3.2 Multi-source Heterogeneous Data Fusion Mechanism

The processing flow of the project's data includes five stages: collection and storage of data, unification of registration, organization of semantics, mapping of resources, and management of versions. The data originations contain drone oblique photograph models, ground laser scanning point clouds, measured height data, archaeology draftings, history research materials, picture resources, sound explanations, and manually made restoration models. All data are undergone the standardized preprocessing before they enter the system, hence resulting in the standardized outputs which are tailored for the follow-up database construction and scenario development.

This project uses a unit projection coordinate system for handling basic survey outcomes, air survey data, and point cloud data. One local scene coordinate mapping is been established for the core site area, in order that it can satisfy twofold requirements for GIS storage and VR engine integration. Partial original data had local offset problems and elevation reference system inconsistencies, which, during the process of development, were corrected via control point calibration, cross-section comparison, and artificial verification[13].

We carry out the statistical analysis on the spatial registration error by utilizing the root mean square error, hence we obtain:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(x_i-\hat{x}_i)^2+(y_i-\hat{y}_i)^2+(z_i-\hat{z}_i)^2\right]}$$

The variables represent the measured coordinates of the i-th control point, hence the values stand for the registered coordinates, hence the total number of control points is given by specification.

With respect to the integration of attribute data, the focal point primarily revolves around the organization of spatial objects. In the stage of database building, the project sets up basic files for every single archaeological site entity, which includes such fields as relic name, category, epoch, space position, archaeology description, document citations, explanation content, and model number label. After the processing step, many kinds of non-space data have connections with space objects, this enables terminal application programs to at the same time take out all connected information when they visit particular objects[14].

Table 3: Statistical analysis of multi-source data processing and database construction results

Data Type	Raw Volume	Processed Objects	Registration Accuracy	Notes
UAV Images	8246 sheets	1 regional model	0.15 m	Overall terrain and ruins surface
Laser Point Cloud	3.6×10^8 pts	42 high-precision units	0.12 m	Walls, foundations, components
Close-range Images	5312 sheets	386 current models	0.10 m	Texture reconstruction
Archaeological Drawings	214 files	386 linked entities	96.2%	Semantic matching
Historical Documents	173 entries	97 restoration entries	94.8%	Reconstruction evidence

The integration of model resources uses a layered management method, and fully considers the following points: models with medium resolution are utilized for overall place environment uses, models with high resolution for current situation and models with high resolution for restoration are kept in key building areas, hence low-polygon models and instance-based processing ways are used for far-distance scenes and repeated components. In the process of database establishment, recovery models bring in documentation fields and version marks for differentiating reconstruction data measured on site and interpretations obtained from experts. The front end at the same time shows edition introductions and connected notes when model is being loaded, hence guarantees content showing keeps clear, complete, and can be tracked.

The data combining work is carried out through programming inside the system, its core logic is shown as below.

Algorithm 1: Pseudocode for Multi-source Heterogeneous Data Fusion and Object Mapping Process

```
Input:
G = geographic datasets
P = point cloud datasets
I = image datasets
D = document datasets
M = restoration model datasets

Output:
DB = integrated spatial database
R = resource mapping table

Procedure DataFusionAndMapping(G, P, I, D, M):
Initialize DB, R
For each dataset g in G:
        g_std <- CoordinateTransform(g)
        g_clean <- TopologyCheck(g_std)
        Insert g_clean into DB.base_geo
```

```
For each dataset p in P:
        p_reg <- PointCloudRegistration(p, DB.base_geo)
        p_mesh <- MeshReconstruction(p_reg)
        Insert p_mesh into DB.current_model

For each dataset i in I:
        i_tex <- TextureGeneration(i)
        Bind i_tex with DB.current_model by object_id

For each document d in D:
        entity <- SemanticExtraction(d)
        obj_id <- SpatialEntityMatch(entity, DB.current_model)
        Insert entity into DB.cultural_info with obj_id

For each model m in M:
        m_opt <- ModelOptimization(m)
        obj_id <- RestorationEntityMatch(m_opt, DB.current_model)
        Insert m_opt into DB.restoration_model
        Insert mapping(obj_id, m_opt, version_tag) into R

Run ConsistencyCheck(DB, R)
Return DB, R
End Procedure
```

3.3 Spatial Database Construction Strategy for Historical Sites

This spatial database is through designing to satisfy the operation demands of visualization systems, it carries out four core functions: object management, resource connection, service releasing, and behavior record keeping. Its beneath structure puts together relation-type data banks together with object deposit. The relation type database stores the structured attribute data, layer information, space indexes, script configuration files, and user operation logs, while the object type storage manages the model files, texture drawings, audio and video resources, and point cloud output results.

The logical construction of this database has five core data sheets. The Fundamental Geography Information Form records district environment data that include landform, water systems, road nets, and function district divisions. The Table of Site Entity Information records the details of objects which include building foundations, archaeological units, excavation positions, and key nodes. The Cultural Description Form includes thing names, time properties, function explanations, archaeology records, origin citations, and explanation words. The Resource Mapping Table makes clear stipulation for model file paths, texture resources, audio/video URLs, and LOD configuration items. The Interaction Script Form has stipulated hot spot trigger conditions, event logics, scene switch parameters, and control instructions for the many-player modes.

Table 4: Core Table Structure and Record Size of Spatial Database

Table Name	Main Fields	Record Count	Function
base_geo_info	id, type, geometry, region	1246	Terrain and environment
ruins_entity_info	id, name, era, location, type	386	Ruins entity indexing
cultural_info	id, entity_id, text, source, audio	521	Cultural interpretation
resource_mapping	id, entity_id, model_path, lod, version	684	Resource dispatch
interaction_script	id, anchor_id, trigger, action	214	Event control

For the promotion of the visualization of historical evolution, the database has brought in period fields, display status fields, and version fields for core archaeological site objects. The objects which have multiple historical stages are managed by multi-version records in a unified main key system, therefore front-end content showing is controlled through period filtering devices. The experiment of the project has proven that stable working performance can be obtained when switching between the existing environment of the site and the reconstruction of historical situations, hence the average time of response which we got is 0.9 seconds for period switching and 1.2 seconds for model version switching.

This database undertakes the collection work of application operation logs as well. Through built-in monitoring points, terminals track user entry regions, stay time, hotspot click actions, cycle switching, model browsing and multi-user cooperation operations, and relevant data are written into the log table in real time. In the 30-day test operation stage, the system has recorded 8,264 user visit logs, 14,372 hotspot clicking events, 6,891 tutorial trigger start actions, 2,176 cycle switching operations, and 84 multi-user cooperation working sessions.

The performance of database query is assessed by utilizing average response delay time, the calculation method is defined as what follows:

$$T_{avg}=\frac{1}{m}\sum_{j=1}^{m} t_j$$

At this place, $t_j$jm stands for the response time that belongs to the nth query request, and it indicates the total quantity of all requests[15]. The outcomes of our tests show that the average time of query response for the database service is 84 ms, and when it is under the peak concurrent condition of 120 users, the average response time is 137 ms.

3.4 Data Organization Specifications for Virtual Reality Scenarios

In the stage of virtual reality scene development, the project has set up unified data arrangement standards, which are carried out in the whole process of resource making and application development. The norms include five respects: level of scene, name of object, packing of resource, setting of hotspot, and arrangement of script, with the goal being to promote the efficiency of resource calling and the ability of later maintenance work.

The architecture of the scene uses a four-layer organization structure. The master control place puts together basic terrain information, whole environment dispositions, navigation systems, and public interaction connection ports. Regional areas correspond to the main function divisions of archaeological relic sites, that manage middle-scale building groups, topic explanation points, and searching paths. Individual construction scenes place emphasis on key structures and heritage cultural objects, which show high-resolution models and localized moving pictures. Detailed scenes display important constituent parts, archaeological cut surfaces, and near-shot objects. In the whole process of development, each level of scene still can be replaced independently, and the transformation between scenes is controlled by a uniform management system.

Table 5: Statistics on VR Scene Organization and Resource Scale

Scene Level	Scene Count	Main Content	Average Package Size
Master Scene	1	Terrain, navigation, global UI	0.9 GB
Regional Scene	8	Functional areas and routes	0.35 GB
Individual Scene	26	Key ruins and buildings	0.18 GB
Detail Scene	41	Components and profiles	0.07 GB

The naming of resources follows unified coding standards. This coding system includes position area codes, target types, target sequence numbers, and edition marks, which can be used for models, textures, scripts, sound files, and narration nodes. The database object identifications are consistent with resource codes, therefore they guarantee high traceability in the whole process of resource obtaining, mistake checking, and edition renewing. In the process of project testing work, 9 resource mapping abnormal situations were discovered and processed, hence making resource calling accuracy keep above 98% after the repair.

The setting of hotspot uses the method that space anchor point and script table drive. Each teaching node, interaction node, transition node and cooperation control node all have independent anchor points set inside the scenario, and trigger conditions, display content and calling logic are all set in the script table through configuration. The scenario model is still kept separate from interaction logic, thus it is enabling the direct configuration renewing for instructional content and logical adjustments. This project has put 132 effective teaching anchor points into use, 56 mutual interaction anchor points, 18 stage conversion anchor points, and 8 cooperation control anchor points, thus it has obtained a script triggering success rate that is 97.9 percent.

4 3D Modeling and Key Technology Implementation

4.1 High-Precision 3D Reconstruction Method for Historical Sites

The 3D modeling work of this project includes two parts: current place rebuilding and past recovery rebuilding. The nowadays reconstruction has the goal to accurately record the present spatial shape of the site, while the history restoration reconstruction puts the focus on reproducing old cultural scenes, therefore it can give support to immersive exhibition activities. Starting from the first development stage, two kinds of modeling results were both carried out standardization processing in coordinate systems, model output rules and naming custom, in order to guarantee the follow-up scene realization can carry out smooth connection integration.

In the present stage of current situation rebuilding, the project has used unmanned aerial vehicle oblique photography to take the overall spatial shape of the archaeological relic site, thus producing a 3D surface model at regional level. Key construct bases, leftover wall bodies, and partial structure members were obtained via ground laser scanning and short-distance photograph shooting, thus producing high-density point cloud groups and high-definition texture picture materials. Through experiencing noise reduction processing, mesh reconstruction, cavity mending, and texture mapping, the original data was changed into a present condition model which is suitable for GIS database integration and VR scene drawing display. The partially covered zones and lost parts were improved according to the measuring outcomes and artificial checking, hence guaranteeing the model's continuous property and visual identifiability in the process of showing.

This historical reconstruction work has been completed on the foundation of archaeological discovered objects, written historical materials, and expert consultation opinions. The modeling work used a layer-by-layer method, in order processed recognizable structure data, guessed building particulars, and extra vision parts while kept matching data information inside the data storehouse. This project at last got out 97 exchangeable repair models, which include 18 whole-size building rebuildings, 52 half structure duplicates, and 27 environment improvement models.

The obtained modeling results were processed with real-time rendering modification before they were put into use. This project has carried out surface reduction processing upon the original high-polygon model, has utilized normal mapping and AO mapping to handle detail information, and thus has conducted texture compression together with atlas integration. The key objects have been given many LOD levels, hence the faraway environments use the simplified netted structures and the instance-based rendering methods.

Table 6: Statistical Results of 3D Model Reconstruction and Optimization

Model Type	Count	Avg Faces Before	Avg Faces After	Optimization Rate
High-precision current model	42	2180000	740000	66.1%
Medium scene model	86	960000	280000	70.8%
Restoration model	97	1340000	460000	65.7%

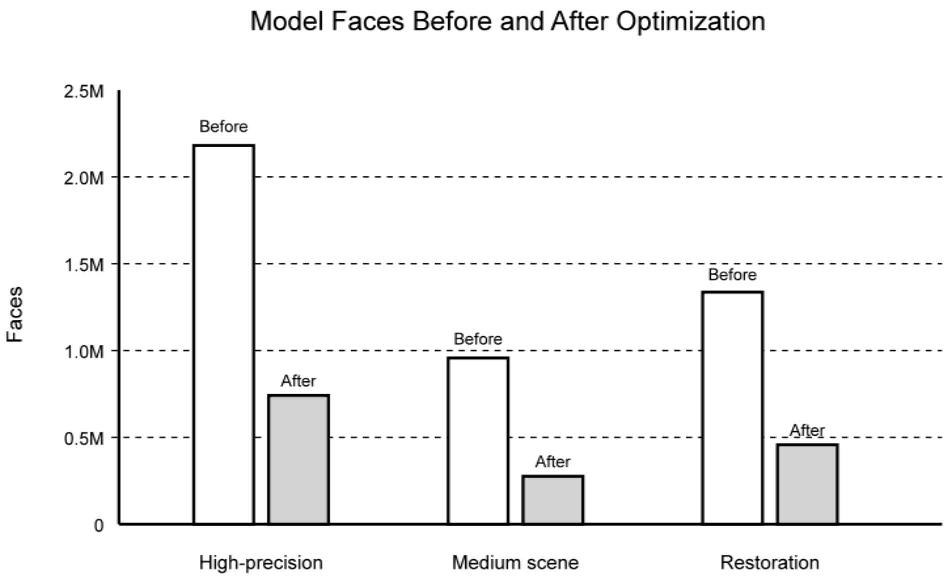

Figure 2: Model Faces Before and After Optimization

4.2 GIS-Based Spatial Data Management and Visualization Engine

This project has developed the GIS module to be the core engine that supports the whole presentation logic. This system has realized unified object management and interactive control among two-dimensional map visual angles, three-dimensional archaeological relic site visual angles, and VR immersion visual angles. In the development process, function modules including base drawing, topic layers, target index, path programming and position search were finished, with integration completed by means of API services and front-end application programs.

One kind of bidirectional synchronization mechanism has been built between the map view and the 3D scene. When users have chosen a concrete archaeology site region on the map's surface interface, the system by itself finds the corresponding 3D scene on the basis of object index and finishes the switching of scene. When one enters a certain building or hotspot region inside the 3D scene, the map interface at the same time makes the object position highlighted and shows the attribute information. This function has shown steady performance when we carried out end testing, the average synchronization response time of 0.7 seconds for the transformation from map to 3D scene and 0.5 seconds for the transformation from 3D scene to map.

This item carries out the function of multi-topic level management inside the GIS engine. The terrain characteristics, water systems, building remains, rebuilt things, archaeology areas, explanation points, and travel paths are all handled as separate layers. This system offers many display modes that contain archaeological view, guided tour view, reconstruction view, the frontend carries out dynamic control over layer visibility and resource obtaining logic in accordance with what user has chosen. The experiments of layer switching have shown that the average response time of ordinary topic switching is 0.6 seconds, hence the average response time of complex topic switching which contains reconstructed objects reaches 1.1 seconds.

The spatial analysis function inside the project mainly plays the role for path navigation and guided tour flow control. This system produces suggested travel paths on the basis of user position and environment setting arrangements, hence it activates corresponding sound explanation devices on important path points. Under the multi-user mode, tour guides or teachers can start pre-set good routes, therefore the system can by itself lead participants to one by one enter and visit key scenic spots. In the experiment testing stage, the path suggestion function was called 1,837 times, hence it obtained a 95.6% successful rate of route deviation correction, and a 96.9% correct rate of navigation node triggering.

Algorithm 2: Path Recommendation and Explanation Node Trigger Logic Pseudocode

```
Input:
current_position
target_zone
graph G(V, E)
hotspot_set H

Output:
path P
triggered_hotspots

Procedure RouteAndGuide(current_position, target_zone, G, H):
start_node <- MatchNearestNode(current_position, G)
end_node <- MatchTargetNode(target_zone, G)
P <- ShortestPath(start_node, end_node, G)

triggered_hotspots <- []
For each node v in P:
        nearby <- SearchHotspots(v, H, radius)
        For each h in nearby:
```

```
                If TriggerConditionMet(h):
                    ExecuteGuideScript(h)
                    Append h to triggered_hotspots
    Return P, triggered_hotspots
    End Procedure
```

The shortest path computation employs a standard path cost function:

$$C(P)=\sum_{e_k \in P} w_k$$

The symbol $Pe_k kw_k$stands for the path aggregate, wherein the i-th side on the path expresses the side weight, which is distributed via an overall assessment of distance, reachability, and interpretation priority.

4.3 Lightweight Rendering Optimization Technology for Mobile VR

When mobile terminals conduct processing on large-scale historical site scenes, they are confronted with relatively great computational and network pressures. In the process of carrying out this work, the item obtained the light-weight improvement in five important directions: model arrangement, texture management, light dealing with, cache methods, and input reaction, therefore finally finished a movable VR working plan which is customized for this system.

The model arrangement uses a mixed method of straight-line vision control and field vision control. Terminals in dynamic way load models that have different levels on basis of user's perspective direction, spatial position, and viewing distance, implement simplifying drawing process for far objects, meanwhile stop drawing or postpone loading for objects which are outside the visual field. Step-by-step progressive loading methods are utilized in important construction regions, with high-accuracy fine particulars being slowly supplemented when users get closer. The experiment result shows that turning on dynamic arrangement on common mobile equipment can cut average scene memory occupation from 1.86 GB to 1.14 GB, and therefore acquire an average frame rate promotion of about 31.7%.

The control of texture is realized by means of three techniques, which are texture compression, atlas integration and localized high-resolution reservation. The compressed atlases are by people utilized for large-scale surfaces, walls, and public environments, therefore to lower the material changing frequency. Key constituent parts and central presentation objects keep separate high-quality texture materials to keep up with fine visual faithfulness when at short distance. Static scene lighting uses the pre-baked treatment, while dynamic objects keep the fundamental real-time lighting, hence it effectively controls the terminal rendering load. The outcomes of our test show that texture compression can cut resource size by an average of 52.4% and thus shorten the time that a scene needs for loading by 21.3%.

This strategy for cache storage combines the local cache storage with the edge cache storage. When terminals at the first time access basic scenes, core resources are written into local caches, therefore this allows direct data obtainment in follow-up visits. The hotspot regions obtain the preferential resource distribution from edge nodes, for the purpose of reducing the cross-area calling delay to the smallest possible extent. The results of our test prove that accessing key areas again and again can lower the average time of loading from 1.9 seconds to 0.8 seconds when in Wi-Fi environments, and from 2.2 seconds to 1.0 seconds when in 5G environments.

Table 7: Performance Comparison Before and After Mobile VR Optimization

Metric	Before Optimization	After Optimization	Improvement
Average FPS (Mobile)	31.9	42.0	31.7%
Average FPS (VR)	46.3	58.4	26.1%
Average GPU Memory/GB	1.86	1.14	38.7%
Texture Package Size/GB	2.48	1.18	52.4%
Revisit Load Time/s	1.9	0.8	57.9%

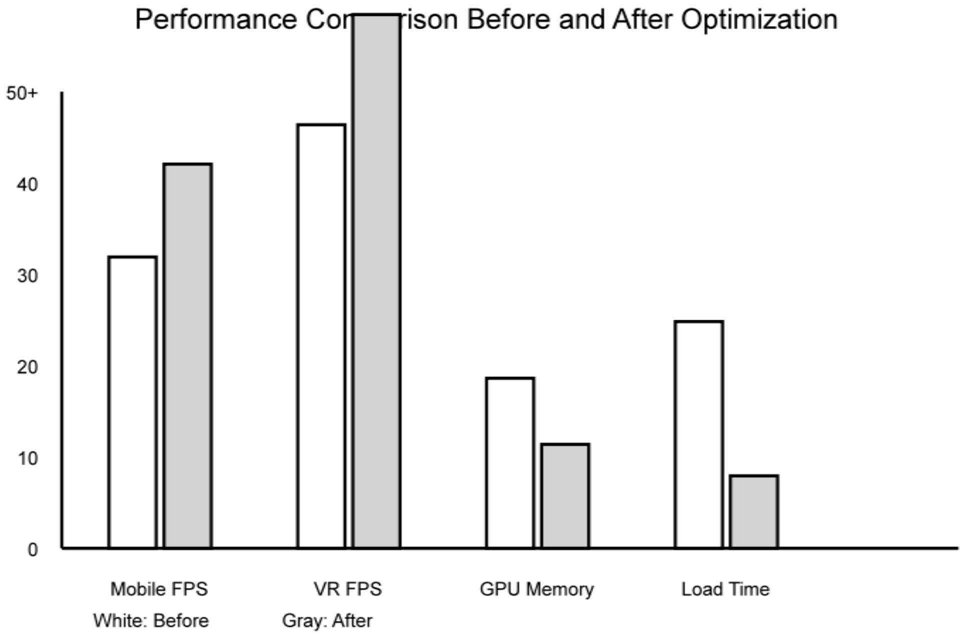

Figure 3: Performance Comparison Before and After Optimization

4.4 Immersive Interaction and Multi-user Collaborative Mechanism

This project has established a unified event-driven mechanism in the domain of interaction design, which maps mobile terminal operations, VR terminal operations and multi-user cooperative operations in a unified way to standardized business events. The terminal differences are handled by the input layer adaptation processing, while the core functions are kept consistent. The processes of system maintenance and function expansion are relatively transparent.

The single-user interaction functions contain free walking, picture zooming, hotspot showing, time changing, model contrasting, and clickable descriptions. Mobile apparatus make use of touch controls to carry out object selection and path navigation, hence VR terminals utilize gaze tracking and controller work operations. When one has entered the interactive area, the system can automatically open the voice explanation, the object highlighting and the function interface display. Key targets let users make exploration on detailed renovation models, part parameter descriptions, and archaeological proofs through enlarged perspectives.

The multi-user cooperate module on the server side realizes room management, status same-step, sound talk, and host control functions. When users go into the same virtual environment, the system carry out synchronization on their real-time position, direction, voice condition, and important operation behaviors. The host still keeps the central control on time transformation, selection of focus object, and the emphasis of key regions. This function has already been put into use in teaching showings and project report meetings, thus it guarantees stable multi-user synchronous operation when people carry out interactive watching and explanation. This project has carried out 84 tests under multi-user mode, among which there are 52 sessions that have 2 to 5 participants, 24 sessions that have 6 to 10 participants, 8 sessions that have more than 10 participants, and the maximum stable capacity of one session is 18 participants.

The synchronous coordination strategy employs a priority management approach. Location data, voice commands, and host control commands are broadcasted in real-time as high-priority information, while routine actions and non-critical interactions are transmitted regionally as low-priority information. The system adjusts synchronization coverage based on the user's geographic location to minimize unnecessary network overhead.

5 System Application and Experience Evaluation

5.1 Implementation of Typical Site Case Applications

This project, with clearly set goals, has successfully finished the display scene work of a historical site and hence has realized the deployment of the application. The on-spot application method acts as a visitor guiding system for the heritage zone, offering core functions including position tracing, path suggestions, interactive explanation starting, and 3D show of important cultural relics. The long-distance application pattern is arranged on education and exhibition terminal devices, providing immersion type virtual visits, era-based direction guiding, model contrast tools, and multi-user synchronous explanation functions. Two application types both run under one united database and resource frame, the difference of functions is realized by terminal compatibility and permission setting arrangements.

In the stage that the system carries out launching test, five core components got examination one after another: basic browse function, hot spot explanation, scene recovery switch, multi-user cooperate work, and back end renewal. Through the 30-day experiment time, the locality working mode has cumulatively served 412 users, the long-distance mode has received 286 users, thus it has obtained that the entire system usable rate is 97.4 percent. High-traffic areas which include key architecture places and environment explanation points have shown that user participation degree is higher, average stay time reaches 4.8 minutes in these key zones, therefore it is compared with 2.1 minutes in common areas. The backstage content management module has already finished many resource refresh cycles, thus it guarantees the smooth deployment of newly added explanation points and model editions.

Table 8: Key Application Data Statistics During the Trial Operation Phase

Item	On-site Mode	Remote Mode	Total
Service Users	412	286	698
Effective Visits	401	279	680
Average Stay Time/min	18.6	22.4	20.2
Key Area Average Stay/min	4.8	5.1	4.9
Multi-user Sessions	12	72	84

5.2 Quantitative Evaluation System for User Experience

This project evaluation has employed a method that combines questionnaire investigation, user conversation talks, and system log analysis. The key evaluation dimensions contain immersion experience, operation usability, content understanding, system stabilization, and communication acceptance. The participant group is constituted by ordinary tourists, students, and working personnel. We altogether distributed 168 questionnaires, and we collected 153 valid replies, hence we got an effective reply rate that is 91.1%. The people who joined our research contain 72 common travel persons, 56 studying persons, and 25 work experts.

We have carried out the quantitative evaluation by utilizing a five-point scale. The formula which is used to calculate the average score is just as below:

$$Score_{avg}=\frac{\sum_{i=1}^{n} s_i}{n}$$

In this place, $s_i$in stands for the score that the i-th subject gets in a particular dimension, and it represents the quantity of effective samples.

According to the comprehensive analysis of comparison results, the existing immersive experience dimension gets an average score of 4.56 points, among which operation usability gains 4.31, content understanding gains 4.62, system stability gains 4.28, and spread acceptance gains 4.49 points, hence it gives a total satisfaction rate of 91.3%. The users have given high praise to the current function of state restoration comparison, the space navigation system, and the integrated interactive commentary. Through interviews we have found that the majority of users can grasp the spatial structure and historical functions of heritage sites effectively by means of this system, thus they display relatively strong acceptance towards the visualized commentary presentation method. Among users of VR terminals, 13 persons have reported mild short-term uncomfortable feelings (8.5%), which mainly take place in the stages of first-time usage.

The project group also carried out evaluation on the system’s effect in promoting knowledge understanding by means of pre-test and post-test methods. We have carried out a comparative research which has 38 student participants, it includes 10 objective questions that assess their grasping of site spatial structures, architectural functions, and historical period judgment. The experiment outcomes have proven that the average scores of participants went from 61.8 points before the system was put into use to 84.6 points after the system was put into use, which reflects a obvious enhancement of 22.8 points.

Table 9: Statistical Results of User Experience Evaluation

Evaluation Dimension	Mean Score	Standard Deviation	Satisfaction/%
Immersion	4.56	0.48	91.2
Ease of Use	4.31	0.57	86.2
Content Understanding	4.62	0.44	92.4
System Stability	4.28	0.61	85.6
Acceptance and Recommendation	4.49	0.50	89.8

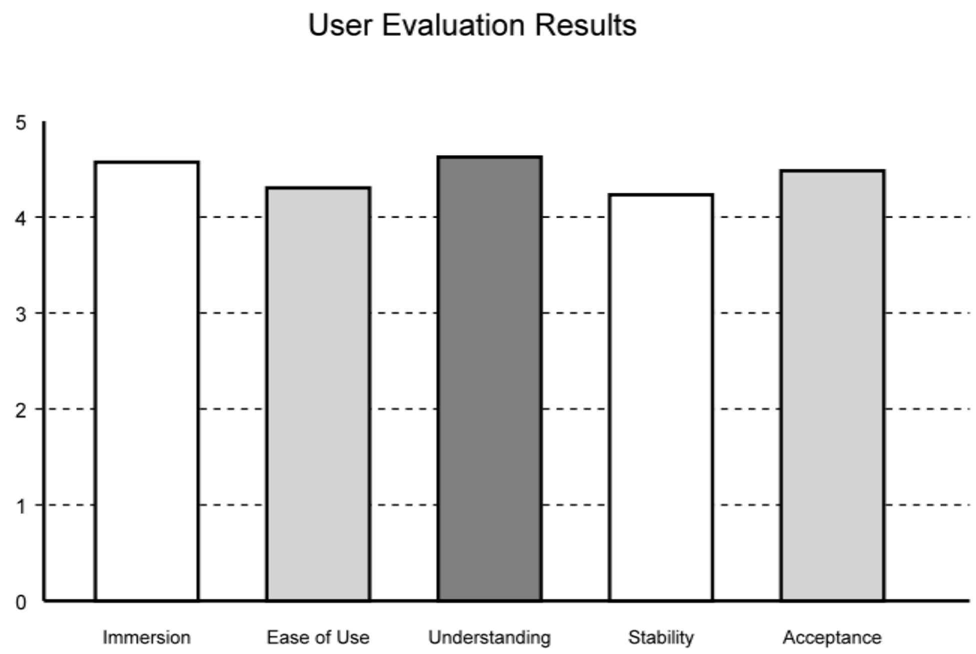

Figure 4: User Evaluation Results

The project group further made use of paired-sample gain rates for the quantification of improvements in knowledge comprehension.

$$G_{learn}=\frac{Score_{post}\text{-}Score_{pre}}{Score_{pre}}\times 100\%$$

The arrangement $Score_{pre}Score_{post}$shows that the average score of pre-test is taken as the average score of post-test. Based on the outcomes of the test, the knowledge comprehension increase rate of student users is 36.9 percent.

5.3 Comparative Analysis of Display Effects

The project group has carried out comparison researches between this system and three show methods: graph-word show boards, normal 3D network interfaces, and independent VR equipment which uses fixed devices. The performance of spatial visualization has shown clear superiorities: the graphic-text modes do well in the presentation of basic knowledge but they display limited capabilities of rendering spatial structure; Standard 3D web interfaces provide basic functions for showing three-dimensional graphs, but they do not have immersive experience and deep interaction; The independent VR systems have good performance in scene rebuilding, but they encounter restrictions in the organization of spatial data and the scalability of content. This system has established a unified framework which includes spatial indexing, scene reconstruction, knowledge correlation and terminal compatibility, therefore it possesses a more comprehensive display logic architecture.

The project group that we set up arranged comparison experiments which have 32 persons to join, using completely same display materials. The results have proven that on the "Spatial Structure Understanding" measuring indicator, the average score that the text plus image mode got is 3.1 points, and after that comes the internet-based 3D mode (3.7 points), the independent VR mode (4.2 points), and the system itself (4.6 points). With regard to the target of "Content Comprehension Efficiency", the four kinds of modes have obtained scores that are 3.4, 3.6, 4.1, and 4.5 separately. With respect to "Interactive Engagement", the score values have a scope from 2.8 to 4.7 in all the modes. With regard to the item of "Repetition Intention", the four kinds of modes got recorded scores 3.0, 3.5, 4.1, and 4.6 separately.

Table 10: Comparative evaluation results of different display modes

Mode	Spatial Understanding	Content Efficiency	Interaction Engagement	Reuse Intention
Graphic Panel	3.1	3.4	2.8	3.0
Web 3D	3.7	3.6	3.3	3.5
Standalone VR	4.2	4.1	4.4	4.1
Proposed System	4.6	4.5	4.7	4.6

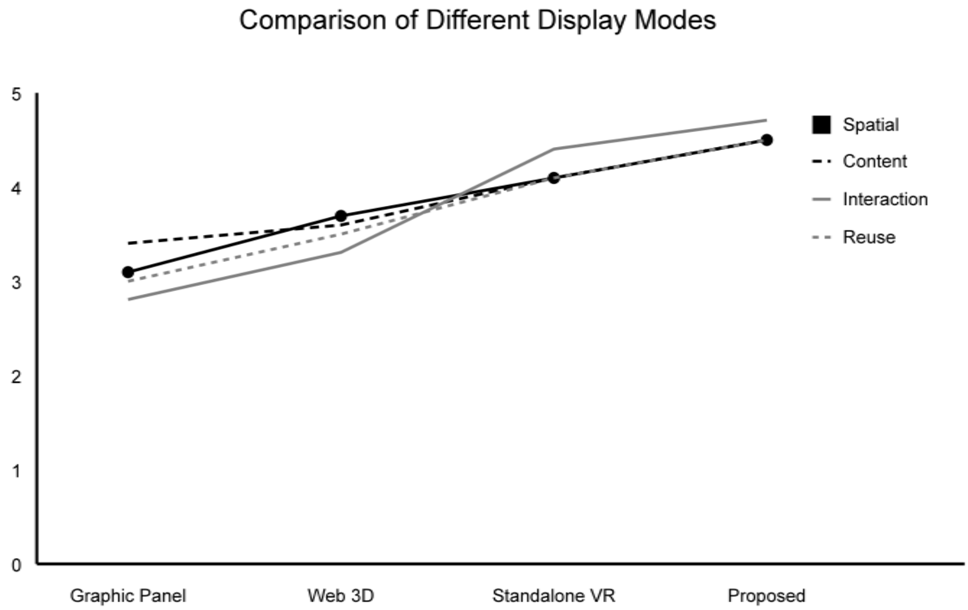

Figure 5: Comparison of Different Display Modes

6 Conclusion

The results that this project has carried out show that a united spatial object coding system, level-by-level scene arrangement mechanism, data resource mapping frame, and light-weight mobile arrangement plan effectively support the steady work of an immersion-type historical relic site exhibition platform. The GIS platform bears the core works which include spatial data arrangement, object index making, route analysis, and layer management, hence the VR module provides immersive place showing and interactive cultural spreading. The deployment plan for mobile network guarantees that the system can be reached on many equipment and the application has anti-destroy ability. The system experiment tests have discovered that the optimal loading efficiency and frame rates are obtained under current common network conditions, hence user assessment results have given out high immersion scores and content comprehension marks. This platform has successfully satisfied various application demands which extend from on-site leading visits to long-distance exhibitions and educational spreading.

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