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Research on the protection and intelligent development path of Hakka Cultural heritage in Henan Province under the empowerment of science and technology

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SUMMARY: *The digital protection of Hakka cultural heritage in Henan Province has the technical foundation of multi-source perception, 3D reconstruction, knowledge mapping and collaborative operation. Focusing on the surrounding buildings, traditional villages, folk objects, oral data and activity scenes, this paper constructs a computing framework that integrates image acquisition, point cloud registration, semantic coding, terminal collaboration and feedback update. A total of 4680 samples of indoor and outdoor images, UAV aerial survey data, laser point clouds and text records were collected, including 3020 groups of architectural images and point clouds, and 1660 groups of text and audio samples. The system achieves 93.6% accuracy of geometric reconstruction, 91.9% of texture fitting and 92.8% of semantic mapping completeness, 93.2% of knowledge retrieval success rate, 91.7% of cross-end call consistency rate, and 90.9% of scene update completion rate. This method realizes the structured storage, scene reconstruction, knowledge association and terminal call of heritage information, and can support the display guide, environmental monitoring, content push and service adjustment synchronously, so that the protection, dissemination and sharing run in the unified computing link. The empirical results show that the framework can enhance the fineness, cross-end collaboration and service ability of Hakka cultural heritage digital expression in Henan Province, and provide technical support for regional cultural resource management.*

KEYWORDS: *Hakka cultural heritage; Digital modeling; 3D reconstruction; Intelligent protection platform*

1 Introduction

1.1 Digital Demand and technological evolution of Hakka cultural heritage protection in Henan Province

The demand for digital protection of Hakka cultural heritage in Henan province is based on the joint promotion of heritage type expansion, spatial distribution dispersion and communication mode renewal. Wave-house buildings, traditional dwellings, genealogy documents, folk custom artifacts, dialect audio and video and festival event records not only carry regional migration memories, but also contain computational image, geometric, semantic and temporal information. Therefore, cultural heritage protection has gradually

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shifted from single archive to the technical stage of data collection, structure modeling and scene expression in parallel.

In the context of continuous evolution of digital technology, 3D modeling, point cloud processing, semantic segmentation, virtual interaction and knowledge organization have become important supports for heritage information representation, and the preservation, display and dissemination of Hakka cultural heritage in Henan Province have also entered a new stage supported by computer technology. Albertini et al. developed PROTEUS, an immersive tool for exploring cultural heritage across spatio-temporal scales, which provides an interactive basis for multi-level digital presentation of heritage scenes [1]. The Gherardini and Sirocchi systems integrate 2D and 3D data sources, realize the virtual reconstruction of lost heritage components, and provide a reference path for the unified modeling of heterogeneous data [2]. Foryś et al. proposed FAMFR high-resolution point cloud registration process to enhance the fineness of multi-mode feature alignment of cultural heritage indoor scenes [3]. Yang et al. systematically sorted out the semantic segmentation of 3D point clouds of cultural heritage, and further explained that geometric recognition and semantic expression have become an important direction of heritage digitization [4]. On the basis of this technology, the protection of Hakka cultural heritage in Henan province no longer stays in static records, but gradually forms a continuous link covering collection, reconstruction, annotation, mapping and service call.

Digital expression can not only preserve architectural scale, component texture, spatial pattern and activity traces, but also transform scattered cultural information into searchable, analysiable and renewable computing resources, so that the protection process and intelligent development process are unified. Based on this, this paper introduces multi-source perception, three-dimensional reconstruction and knowledge mapping methods to promote the evolution of Hakka cultural heritage in Henan Province from physical retention to digital retention and from single point display to platform collaboration. Acquisition terminals, database interfaces, visualization platforms and mobile devices were incorporated into a unified technical system, forming an operational structure linking content convergence, status feedback and application distribution. The digital needs of Hakka cultural heritage in Henan Province were further extended from display and preservation to academic arrangement and public access.

1.2 The integration logic of Hakka cultural heritage protection and intelligent computing technology

The integration of Hakka cultural heritage protection and intelligent computing technology does not attach digital tools to the display link, but integrates collection, identification, modeling, annotation, dissemination and feedback into the same computing link. The Hakka walled houses, traditional settlements, worship Spaces, vessel patterns and oral data in Henan province not only have spatial forms, but also contain rich semantic levels and media information. Therefore, digital protection needs to be supported by image computing, 3D reconstruction, knowledge organization and interactive engine. Abergel et al. studied the collaborative documentation process of cultural heritage objects and proposed Aioli realistic 3D annotation cloud platform, which puts 3D models, semantic annotation and multi-user collaboration in a unified environment, and provides a technical path for dynamic labeling and sharing of heritage materials [5]. Wang et al. studied the application of immersive virtual reality and computer vision in the visual evaluation of heritage, and proposed a perception analysis method for industrial heritage scenes, so that visual restoration and spatial cognition could be completed in the same interface [6]. Chen et al. studied the use behavior of augmented reality in heritage museums and proposed an interactive interpretation framework from the perspective of socio-technical, indicating that the operation effect of heritage digital services is closely related to content organization, interface design and user acceptance [7]. Wang et al. studied the Transformer-enhanced point cloud registration method, and proposed a high-precision alignment mechanism suitable for the protection scene of Terracotta warriors, which enhanced the stability of complex heritage components in geometric matching and detail recovery [8].

On the basis of these studies, the intelligent protection of Hakka cultural heritage in Henan Province can form a continuous processing process from multi-source data input to spatial reconstruction, from semantic mapping to terminal interaction, so that architectural forms, decorative details, ethnic memory and activity scenes can be computationally represented in the digital environment, and support applications such as display guide, remote access, knowledge service and state response. In this paper, the intelligent computing technology is embedded into the process of Hakka cultural heritage protection, so that the preservation, invocation and dissemination of cultural resources maintain a unified technical logic. In actual operation, the platform can adjust the rendering accuracy and service mode according to the access terminal, environmental status and content type. The mobile terminal focuses on browsing and path guide, the desktop terminal focuses on detail retrieval and academic comparison, and the immersive terminal focuses on space roaming and scene experience. Therefore, the intelligent development of Hakka cultural heritage is based on computing that can be perceived, analyzed, updated and has cross-platform collaboration capabilities, which extends digital protection to application levels such as resource management, content dissemination and public services.

1.3 Multi-terminal sensing and Interactive Applications for smart Development

The multi-terminal perception and interactive application for intelligent development needs to unify the spatial information, historical content and access behavior of Hakka cultural heritage into a computable environment, rather than staying in a single display terminal. The Hakka enclosed houses, traditional streets, family migration nodes and folk activity scenes in Henan province have obvious regional connections and time levels. After access, mobile terminals, web terminals, immersive terminals and monitoring terminals can respectively undertake tasks such as navigation and browsing, knowledge retrieval, scene experience and state collection, so that cultural resources can be continuously used under different use situations. Tian et al. studied the virtual museum based on dual-mode hybrid visualization, and proposed a display method that takes into account both realistic presentation and interactive understanding, which provides experience for the collaborative expression of cultural relic content in multi-terminal environment [9]. Hidalgo-Sanchez et al. studied the digital reactivation process of geospatial cultural routes, and proposed the VIDA-HTL network application, which integrated spatial routes, cultural nodes and user access into the same platform, providing a reference for the network transmission of regional cultural resources [10]. Liu et al. studied the application trend of GIS in cultural heritage protection and proposed a comprehensive application framework from spatial analysis, risk identification to resource management, indicating that geographic information processing has become an important support for intelligent management of heritage [11]. Mu et al. studied the method of H-GIS and H-BIM to simulate urban evolution, and proposed a historical scene modeling path considering both time dimension and spatial structure, which provided a technical basis for dynamic reappearance of heritage environment [12].

On this basis, the multi-terminal interaction of Hakka cultural heritage in Henan province is no longer the change of interface form, but the synchronous extension of data organization mode and service logic. The 3D model, image texture, voice explanation, dialect data and genealogy text can be distributed through a unified interface, and the rendering accuracy, information level and interaction mode can be switched according to the terminal computing power, network status and access target. The mobile terminal is suitable for lightweight navigation and route recommendation, the web terminal is suitable for data access and special display, the immersive terminal is suitable for space roaming and scene perception, and the environmental monitoring terminal continuously transmits temperature, humidity, light and passenger flow status, so that the platform can complete content update and display adjustment. In this paper, multi-terminal perception, spatial computing and interactive services are combined to form a unified link between digital preservation, public communication and intelligent services of Hakka cultural heritage in Henan Province, and to provide computer technical support and interface collaboration capabilities for the fine management and sustainable use of regional cultural resources.

2 Related work

The research on digitization of cultural heritage has gradually shifted from pure recording to collaborative promotion of perception collection, 3D modeling, semantic organization and intelligent services. Artificial intelligence visual recognition, HBIM, point cloud processing, ontology modeling and platform call continue to enter the heritage protection scene, so that heritage objects are no longer just static preservation materials, but are transformed into data resources that can be collected, calculated, updated and invoked. For the Hakka cultural heritage in Henan province, the research objects include not only the wave-house buildings, traditional settlements and utensils patterns, but also the dialect audio, genealogy text and folk custom active images. Therefore, related research needs to pay attention not only to the digital reconstruction of spatial scenes, but also to knowledge expression, terminal adaptation and service extension. Mishra et al. studied the visual inspection of cultural heritage and proposed an artificial intelligenceassisted image interpretation framework, which incorporated the identification of cracks, weathering and surface damage into the computer vision process [13]. Intrigila et al. studied the HBIM modeling of structural heritage and proposed a conservation process oriented to tower heritage, so that geometric information, structural status and maintenance records could be organized in a unified model [14]. Lombardi and Rizzi studied the fusion path of semantic modeling and HBIM, and proposed a multidisciplinary collaborative workflow to enable the heritage model to have knowledge expression ability [15]. Buldo et al. studied semantic enhancement of architectural heritage point clouds and proposed a point cloud classification process based on artificial intelligence, which promoted point clouds from spatial records to component identification and attribute stratification [16].

In order to more clearly sort out the differences in the types of methods, main findings and scope of application of existing studies, the relevant literature is summarized in Table 1.

Table 1: Review of related work

Ref.	Method	Main Findings	Applicability Boundaries
[13]	AI-assisted visual inspection	It can improve the consistency of identifying cracks, weathering, and surface damage.	The effectiveness is influenced by annotation quality and scene differences.
[14]	HBIM-based conservation workflow for structural heritage	It can incorporate component information, structural conditions, and maintenance records into a unified model.	The input of irregular components depends on high-precision preprocessing.
[15]	Collaborative workflow of semantic modeling and HBIM	It can improve heritage data reusability and cross-disciplinary interpretability.	The construction of semantic rules requires stable ontology constraints.
[16]	AI-based semantic enhancement of point clouds	It can improve component recognition and the accuracy of spatial representation.	Occluded regions and fine-detail noise affect classification stability.
[17]	Large-scale point cloud completion network	It can improve the presentation and complete representation of damaged regions.	The results depend on the distribution of training samples.
[18]	Method for converting point clouds into intelligent model sets	It can form a continuous conservation data chain.	Synchronous updating of multiple models requires high platform computing power.
[19]	Metadata and ontology concept model	It can improve the efficiency of knowledge retrieval and semantic association for collections.	Cross-collection mapping still requires unified description standards.
[20]	Shape-grammar-based synthetic point cloud generation	It can supplement samples for training and analysis.	The generated data still require scale calibration with real scenes.

It can be seen from Table 1 that the current related research roughly forms three types of technical routes. The first type of research focuses on legacy morphological computing, focusing on point cloud acquisition, registration, completion, segmentation and intelligent modeling. Li et al. studied the missing completion of large-scale laser point clouds and proposed the missing area completion network, which provided a calculation method for the transparent display and complete expression of the damaged area [17]. Crisan et al. studied the transformation from point cloud to intelligent model set, proposed a model organization method for protection work, and showed that 3D data, attribute data and analysis model can form a continuous call structure [18]. This kind of research is suitable for solving the digital reconstruction and form restoration of Hakka walled house, dwelling house and settlement space in Henan Province. The second type of research focuses on knowledge representation and semantic organization. Zhang and Ren studied ancient ceramic metadata and ontology expression, and proposed a conceptual model to expand the semantic organization mode of heritage resources [19]. This path has a strong reference significance for the structural expression of Hakka genealogy literature, artifact classification, spatial function and migration memory. The third line of research focuses on training sample expansion and structure recognition support. Battini et al. studied the generation of synthetic point clouds of historical vaults, and proposed an analysis and segmentation method based on shape grammar, which provided a new path for training data expansion and structure analysis [20]. This idea also has reference value for the digital processing of Hakka cultural heritage with scattered sample sources and obvious morphological differences.

Based on the existing results, it can be found that relevant research has formed a relatively clear technical foundation in visual recognition, point cloud computing, HBIM integration and knowledge modeling. However, most of the research objects focus on single buildings, single collections or specific exhibition Spaces, and the unified coding of cross-type heritage data, multi-terminal interactive services and platform cascasive organization are less involved. Hakka cultural heritage in Henan province has the complex characteristics of the coexistence of architectural entities, spatial environment, textual knowledge and activity records. The digital protection process requires not only geometric modeling capabilities, but also semantic mapping, interface collaboration and service scheduling capabilities. Based on this research background, this paper integrates multi-source collection, 3D modeling, knowledge mapping, terminal collaboration and feedback update into the unified computing framework, which makes the Hakka cultural heritage in Henan Province form a continuous link between digital preservation, knowledge organization, display and communication, and intelligent service, and provides direct support for subsequent method design.

3 Research Methods

3.1 Multi-source data collection and digital modeling of Hakka cultural heritage in Henan Province

The multi-source data collection and digital modeling of Hakka cultural heritage in Henan province are the basic process of transforming the wave-house buildings, traditional settlements, vessel patterns, genealogy texts, dialect audio and moving images into unified computing objects. In this paper, a processing link of "image acquisition-point cloud reconstruction-semantic coding-schema association" is adopted, and UAV aerial survey, ground laser scanning, mobile photogrammetry, environmental sensing recording and text file input are synchronously connected in the field acquisition stage, so that spatial information, visual information and cultural semantics are mapped in the same data framework.

In order to ensure the stable connection between the collection, calibration, coding and modeling of Hakka cultural heritage data, this paper builds a multi-source driven digitization process, as shown in Fig. 1.

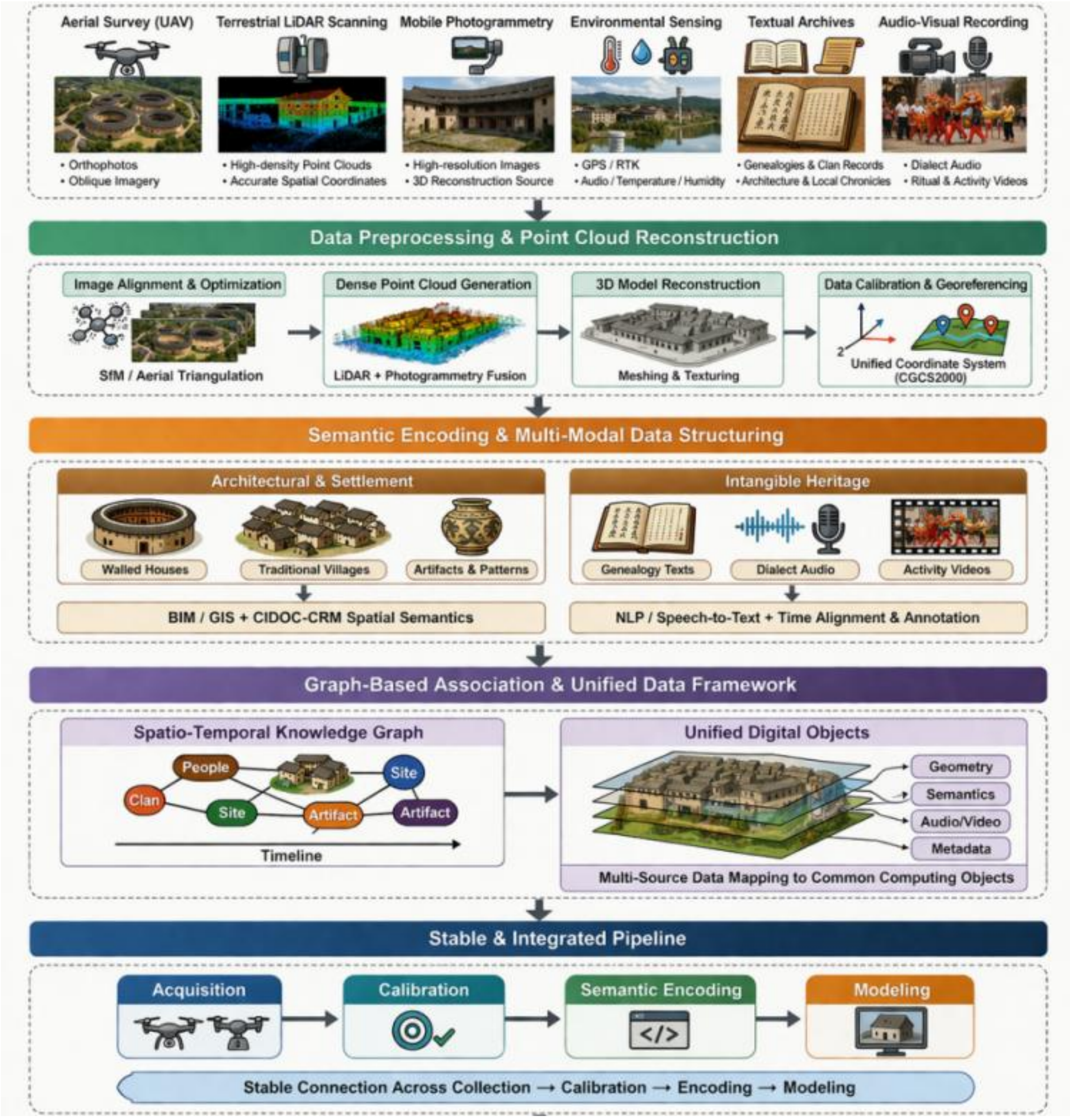

Figure 1: Process of multi-source data collection and digital modeling of Hakka cultural heritage in Henan Province

In order to achieve a unified expression of images, point clouds, text and environment sequences in the same feature space, this paper first maps and concatenates different modal data to obtain the composite input vector of the heritage object, which is calculated as follows:

$$x_i = \phi\left(W_v f_v(I_i) \parallel W_p f_p(P_i) \parallel W_t f_t(T_i) \parallel W_e f_e(E_i)\right) \quad (1)$$

where x_i represents the unified feature vector of the i heritage object. I_i, P_i, T_i and E_i represent image, point cloud, text and environment sequence inputs, respectively. W_v, W_p,W_t and W_e denote the mapping matrices of each modality. Let $\phi(\cdot)$ denote the fusion function. The function of Equation (1) is to compress multi-source heterogeneous data into a unified representation space, which provides a consistent input for subsequent graph structure modeling and semantic association calculation.

After the completion of multi-modal unified coding, this paper further combines spatial adjacency and time continuity information to propagate and update the status of legacy nodes. The calculation form is as follows:

$$z_i = \sigma\left(W_x x_i + W_h \sum_{j \in \mathcal{N}(i)} \alpha_{ij} x_j + b\right) + \lambda r_i \tag{2}$$

where z_i represents the updated state vector of the node. x_i represents the node input features; $\mathcal{N}(i)$ represents the neighborhood set of nodes; α_{ij} represents the association weights between nodes; r_i denotes the spatio-temporal residual term; Let λ denote the residual adjustment coefficient. The function of Equation (2) is to integrate the self-information, neighborhood information and spatio-temporal continuous information of the current heritage node, so as to maintain the structural association of architectural components, spatial scenes and cultural nodes in the dynamic update.

In order to accurately describe the correlation strength between different nodes in spatial distance and cultural semantics, this paper calculates the edge weight in the graph structure by normalizing, and its expression is as follows:

$$\alpha_{ij} = \frac{\exp\left((Qx_i)^{\top}(Kx_j)/\sqrt{d} + \beta s_{ij} + \gamma m_{ij}\right)}{\sum_{k \in \mathcal{N}(i)} \exp\left((Qx_i)^{\top}(Kx_k)/\sqrt{d} + \beta s_{ik} + \gamma m_{ik}\right)} \tag{3}$$

Here, α_{ij} represents the normalized weight between node i and node j. Q and K represent the query matrix and the key matrix. d is the feature dimension; s_{ij} denotes the spatial distance constraint; m_{ij} denotes semantic similarity; Let β and γ denote the weight coefficients of the two types of constraints. The function of Equation (3) is to jointly introduce the geometric position relationship and cultural semantic relationship into the edge weight allocation process, so that the association between Hakka wave-houses, objects, texts and active nodes is established on multiple information constraints.

After completing feature representation, node update and edge weight construction, this paper uses a joint loss function to optimize geometric reconstruction, semantic recognition, texture restoration and relational mapping in a unified way, which is of the following form:

$$\mathcal{L} = \eta_1 \|\hat{V} - V\|_2^2 + \eta_2 \sum_{c=1}^{C} y_c \log \hat{y}_c + \eta_3\left(1 - \mathrm{SSIM}(\hat{I}, I)\right) + \eta_4 \|A - \hat{A}\|_F^2 \tag{4}$$

Here $\mathcal{L}$ represents the overall optimization objective; $\hat{V}$ and V denote the reconstructed geometry result and the true geometry; $\hat{y}_c$ and y_c represent the predicted and true labels; $\mathrm{SSIM}(\hat{I}, I)$ represents the structural similarity of texture reconstruction; A and $\hat{A}$ denote the true and predicted correlation matrices; $\eta 1$ to $\eta 4$ represent the weight of each loss term. The function of Equation (4) is to put the modeling objectives of geometric layer, semantic layer, texture layer and relationship layer into the same optimization framework, so as to ensure the consistency of the digital results of Hakka cultural heritage in Henan Province in form reduction, semantic expression and knowledge link.

Firstly, the real image is processed by distortion correction and illumination normalization, the point cloud data is denoised, registered and transformed into grids, and the text and speech data are entered into the knowledge base through word segmentation, transcription and entity extraction. After the different modalities are aligned with a unified timestamp and spatial coordinates, they are fed into the feature fusion layer to generate composite representations oriented to architectural units, spatial scenes and cultural nodes. The data modeling not only preserves the scale, material texture and spatial relationship of components, but also encodes the clan information, ritual names, usage functions and historical events into searchable semantics, so that the subsequent 3D reconstruction, knowledge mapping and terminal call are established on a unified base.

3.2 Virtual interaction and intelligent response mechanism for smart protection scenarios

The intelligent protection scenario of Hakka cultural heritage is not a simple online display, but organizes space roaming, knowledge retrieval, state perception and service feedback into the same interactive link. The call of Hakka-enclosed houses, traditional settlement, worship space and folk activities in Henan province in the digital environment should not only maintain the continuous expression of historical information, but also adapt to the differentiated access between mobile terminals, web terminals and immersive terminals. Therefore, this paper takes virtual interaction and intelligent response mechanism as the core link of the platform operation. The system first generates interaction states based on user location, browsing depth, terminal capabilities, and content type. In order to depict this process, this paper jointly encodes the location feature, behavior feature, terminal state and the interaction result at the last moment, and its calculation form is as follows.

$$u_t = \tanh\left(W_l l_t + W_b b_t + W_q q_t + W_g u_{t-1} + b_u\right) \tag{5}$$

Here, u_t represents the interaction state vector at time t, l_t represents the location feature, b_t represents the behavior feature, q_t represents the terminal capability feature, u_{t-1} represents the state at the previous time, and W_l, W_b, W_q and W_g represent the mapping matrix. The function of Equation (5) is to compress the current access state into a unified expression and provide input for subsequent response scheduling.

After obtaining the interaction state, the platform needs to judge the display order and call intensity of different scene nodes. The entrance of the enclosure, the hall, the patio, the ancestral hall and the artifacts display area assume different information densities during the visit process. Therefore, the system calculates the response priority according to the node status and the visit intention, and its expression is:

$$\pi_k = \frac{\exp(a^\top \tanh(W_s s_k + W_u u_t) - \mu \ell_k)}{\sum_{j=1}^{K} \exp\left(a^\top \tanh(W_s s_j + W_u u_t) - \mu \ell_j\right)} \tag{6}$$

Here, π_k represents the response priority of the k node, s_k represents the node content feature, ℓ_k represents the current node load level, u_t represents the current interaction state, and μ represents the load suppression coefficient. Equation (6) is used to determine the display order and service weight of different legacy nodes.

After the node priority is determined, the system needs to update the view Angle and guide the path according to the user's current position and the target area, so that the space roaming is continuous and smooth. To this end, this paper constructs the viewpoint update model as follows.

$$p_{t+1} = p_t + \delta_t \left(R_t v_t + \sum_{m=1}^{M} \omega_m \left(g_m - p_t \right) \right) \tag{7}$$

Here, p_{t+1} represents the viewpoint position at the next time, p_t represents the current viewpoint, R_t represents the orientation rotation matrix, v_t represents the motion vector, g_m represents the candidate guide target, ω_m represents the target weight, δ_t represents the step parameter. The function of Equation (7) is to control the perspective migration and guide path update in the virtual scene.

In order to form an accurate correspondence between the user click content and Hakka culture knowledge nodes, the system also needs to consider semantic similarity and spatial correlation at the same time. In this paper, the joint matching method is used to calculate the correspondence strength between the query item and the legacy node, and the expression is as follows.

$$s_{ij} = \frac{(M_q q_i)^{\top} (M_n n_j)}{\|M_q q_i\|_2 \, \|M_n n_j\|_2} + \rho \, \mathrm{IoU}(r_i, r_j) \tag{8}$$

where s_{ij} represents the matching score between query item i and knowledge node j, q_i represents the user semantic query, n_j represents the legacy knowledge node, ρ represents the spatial constraint coefficient, and $\mathrm{IoU}(r_i, r_j)$ represents the region overlap degree. The function of Equation (8) is to incorporate semantic association and spatial location into the content matching process at the same time.

When the system completes content matching, it needs to select specific response actions according to terminal load, service revenue and current status, such as HD rendering, voice push, knowledge popup or cache switching. To this end, this paper uses a dynamic response distribution model:

$$\pi(a_t|u_t) = \frac{\exp\left(w_{a_t}^{\top} u_t - \kappa l_t + \xi g_t\right)}{\sum_{a \in \mathcal{A}} \exp(w_a^{\top} u_t - \kappa l_t + \xi g_t)} \tag{9}$$

Here, $\pi(a_t|u_t)$ represents the probability of selecting action at in state u, l_t represents the current load level, g_t represents the service benefit term, κ and ξ represent the regulation coefficients, and $\mathcal{A}$ represents the action set. The function of Equation (9) is to realize the dynamic allocation of service actions such as display, push, switch and cache.

Through the above processing, the platform can form a continuous closed loop between user entry, node switching, content retrieval and service execution, so that the digital display, knowledge service and wisdom protection of Hakka cultural heritage in Henan province are built on a unified computing logic. This mechanism not only retains the immersive expression of the spatial scene, but also ensures the coordination of the terminal call and the platform response.

3.3 3D reconstruction and knowledge mapping method of Hakka cultural heritage scene

The 3D reconstruction of Hakka cultural heritage scene does not simply model the encloses, halls and artifacts, but puts geometric morphology, component relationship and cultural semantics into the same computing link. Based on point cloud, image, archival text and family tree data, this paper adopts a continuous method of "point cloud registration, mesh reconstruction, semantic stratification and knowledge mapping". The related research provides a technical basis for reference in the aspects of structural heritage modeling, semantic modeling and HBIM fusion, point cloud semantic enhancement, missing area completion, point cloud to intelligent model transformation, ancient artifact metadata expression, and historical building form analysis, and also provides a method reference for 3D reconstruction and knowledge mapping in this paper.

To illustrate the processing focus of 3D reconstruction and knowledge mapping in different stages, the core links are shown in Table 2.

Table 2: Core processing links of 3D reconstruction and knowledge mapping

Stage	Input	Processing	Output
Point Cloud Reconstruction	Point clouds, images	Registration, completion	Initial model
Mesh Optimization	Initial model	Simplification, texturing	Scene model
Semantic Layering	Component nodes	Classification, annotation	Semantic layer
Knowledge Mapping	Archival texts	Extraction, association	Index graph

In order to make the scene geometry coding, node relationship determination and knowledge graph mapping complete in sequence in the same link, the key computing relations are expressed as follows.

After the point cloud is aligned with the texture, the system first builds a unified scene representation:

$$v_i = \psi(W_p p_i + W_m m_i + W_t t_i) \tag{10}$$

Here, v_i represents the unification vector of the i component, and p_i, m_i, and t_i represent the point cloud, mesh, and texture features, respectively. Equation (10) is used to complete the scene geometry coding.

After the geometric representation is formed, the system further computes the node topological relations:

$$r_{ij} = \frac{\exp(-\tau d_{ij} + \omega c_{ij} + \zeta q_{ij})}{\sum_{k \in \mathcal{N}(i)} \exp(-\tau d_{ik} + \omega c_{ik} + \zeta q_{ik})} \tag{11}$$

Here, r_{ij} represents the node association weight, d_{ij} represents the spatial distance, c_{ij} represents the component co-occurrence relationship, q_{ij} represents the functional semantic similarity. Equation (11) is used to simultaneously characterize spatial and semantic relations.

On this basis, historical archives, family tree information and scene nodes are written into the knowledge graph structure:

$$\mathcal{G} = \{(e_a, \rho_{ab}, e_b) \mid \rho_{ab} = \chi(H_a, H_b, S_{ab})\} \tag{12}$$

Here, $\mathcal{G}$ represents the knowledge graph, e_a and e_b represent entity nodes, and ρ_{ab} represents entity relationships. Equation (12) is used to realize the unified mapping between 3D scene and historical knowledge.

Through the above processing, the entrances, halls, ancestral halls and artifacts can also be associated with family information, purpose instructions and activity records after the fine reconstruction, so that the Hakka cultural heritage scene has the ability of spatial reduction and knowledge organization, and provides a unified data base for subsequent display and call, guide distribution and intelligent services.

3.4 Collaborative Application of intelligent sensing terminal in heritage display and environmental monitoring

The collaborative application of intelligent sensing terminal in heritage display and environmental monitoring is not to connect sensors to the display space, but to put terminal acquisition, state judgment and platform writeback into the same operating link. The Hakka weed-houses, traditional halls, ancestral halls and utensils exhibition areas in Henan province have the characteristics of dense display nodes and subtle environmental changes. Therefore, this paper takes lighting, temperature and humidity, passenger density and terminal load as collaborative control objects to make the display service and environmental monitoring run synchronously. The mobile terminal is responsible for voice push and path prompt, the fixed terminal is responsible for environment collection, the edge node is responsible for local calculation, and the platform is responsible for overall scheduling. The key processing links are shown in Table 3.

Table 3: Collaborative processing links of intelligent sensing terminals

Terminal Type	Input Information	Main Processing	Output Results
Mobile Terminal	Location, clicks, dwell time	Navigation matching	Page response
Fixed Terminal	Illumination, temperature and humidity, visitor flow	State acquisition	Monitoring results
Edge Node	Multi-source sensor data	Fusion-based decision	Control commands
Platform Side	Terminal status, historical records	Scheduling update	Service distribution

In order to make the display call, environment recognition and terminal linkage run continuously in the same framework, this paper expresses the process of state fusion, exception determination and co-scheduling as follows.

The system first fuses the multi-terminal inputs to obtain the scene state vector:

$$S_t = \phi(W_l L_t + W_h H_t + W_f F_t + W_d D_t + b_s) \tag{13}$$

Here, S_t represents the scene state, L_t represents the illumination input, H_t represents the temperature and humidity input, F_t represents the passenger flow characteristics, and D_t represents the terminal load. Equation (13) is used to represent the real-time state.

After state fusion, the platform continues to calculate the anomaly strength of the environment:

$$R_t = \sigma(\alpha \|S_t - \bar{S}\|_2 + \beta \Delta L_t + \gamma \Delta H_t) \tag{14}$$

Here, R_t represents the anomaly score, $\bar{S}$ represents the historical mean state, ΔL_t represents the illumination offset, and ΔH_t represents the temperature and humidity offset. Equation (14) is used to identify environmental fluctuations.

After the anomaly score is obtained, the system allocates cooperative actions combining terminal benefits and response costs:

$$P(a_t|S_t) = \frac{\exp(w_a^T S_t - \mu c_t + \nu g_t)}{\sum_{a \in A} \exp(w_a^T S_t - \mu c_t + \nu g_t)} \tag{15}$$

Here, $P(a_t|S_t)$ represents the probability of selecting action a_t, c_t represents the execution cost, g_t represents the service benefit, and A represents the set of actions. Equation (15) is used to complete terminal co-scheduling.

Based on the above mechanism, the illumination adjustment, explanation push and environmental early warning in heritage display can maintain linkage, so that the display service and condition monitoring of Hakka cultural heritage in Henan province are established on a unified data structure and calculation logic.

3.5 User Experience and Feedback Analysis in Intelligent Service Platform

User experience in smart service platform is not a simple superposition of interface look and feel and operation convenience, but the result of access fluency, content matching, path continuity, cognitive absorption and feedback writeback ability. The digital display of Hakka cultural heritage in Henan province includes house scene browsing, object node retrieval, dialect audio call and history description linkage. Different terminals have obvious differences in screen size, rendering ability and network status, so the platform needs to dynamically adjust the content organization method according to user behavior and device status. Firstly, the platform jointly encodes response delay, interaction depth, semantic hit rate and terminal state into an experience state vector, which is expressed as follows.

$$e_t = \tanh(W_r r_t + W_i i_t + W_m m_t + W_d d_t + b_e) \tag{16}$$

Here, e_t represents the experience state at time t, r_t represents the response delay, i_t represents the interaction depth, m_t represents the semantic hit rate, and d_t represents the terminal state. Equation (16) is used to form a unified experience representation. The mobile terminal is more suitable for lightweight navigation and voice prompts, the web terminal is more suitable for data comparison and knowledge retrieval, and the immersive terminal is more suitable for space roaming and local detail observation. In order to keep the access process stable, the platform continuously records the dwell time, click density, view switching frequency, retrieval path and task completion, and converts these behaviors into experience characteristics.

After obtaining the experience state, the system further calculates the immersion score, which is used to judge the degree of fit between the current display process and the user's access goal, and its expression is as follows.

$$I_t = \sigma(\alpha_1 \|e_t\|_2 + \alpha_2 c_t + \alpha_3 p_t - \alpha_4 l_t) \tag{17}$$

Here, I_t represents immersion score, c_t represents content continuity, p_t represents path smoothness, and l_t represents loading overhead. Equation (17) is used to assess the immersion level. The platform also needs to identify the cognitive load during browsing, which is expressed as follows.

$$B_t = \frac{1}{Z_t} \sum_{k=1}^{K} \exp(\beta_1 n_k + \beta_2 s_k - \beta_3 h_k) \tag{18}$$

Here, $B_t$represents the cognitive load score, n_k represents the number of information nodes, s_k represents the semantic span, h_k represents the familiarity of historical access, and Z represents the normalization term. Equation (18) is used to describe the influence of information density on the understanding process. Immersion and cognitive load together determine whether the current service needs to be adapted.

After the platform completes the experience determination, the feedback strength needs to be generated according to the user feedback, page stay and task completion results, and its expression is as follows:

$$F_t = \gamma_1 q_t + \gamma_2 y_t + \gamma_3 u_t - \gamma_4 a_t \tag{19}$$

Here, F_t represents the feedback strength, q_t represents the subjective rating, y_t represents the task completion rate, u_t represents the willingness to repeat access, and a_t represents the number of interruptions. Equation (19) is used to comprehensively characterize the user feedback effect. The system then writes the feedback back to the service policy, which is updated as follows:

$$M_{t+1} = \lambda M_t + (1 - \lambda)(W_f F_t + W_s e_t) \tag{20}$$

Here, M_{t+1} represents the updated service memory, M_t represents the current memory state, F_t represents the feedback strength, e_t represents the experience state, and λ represents the memory retention coefficient. Equation (20) is used to complete the platform policy update.

Through the above processing, the association between the enclosure space, historical events, family information and folk activities can be continuously optimized with the visit process, so that the intelligent service platform has the ability of display, analysis and feedback regulation.

4 Analysis of results

4.1 Analysis on digital protection Effect and historical information Restoration of Hakka Cultural Heritage in Henan Province

The digital protection effect of Hakka cultural heritage in Henan province is not only reflected in the visual presentation of scene surface, but also reflected in the synchronous restoration of spatial structure, component texture, historical information and cultural semantics. After the completion of multi-source collection and unified modeling, the architecture of the enclosure, the layout of the hall, the furnishings of the ancestral hall, the details of the objects and the activity nodes can enter the digital environment with high accuracy, and form a searchable, comparable, and callable cultural resources. The platform test uses 4680 groups of effective samples, including 3020 groups of architectural image and point cloud samples, 1660 groups of text and audio samples. The system achieves 93.6% in geometric reconstruction accuracy, 91.9% in texture fitting, and 92.8% in semantic mapping integrity, respectively, indicating that the spatial representation and knowledge representation of Hakka cultural heritage have been stable and consistent in the same computing link. As shown in Fig. 2, the three core scenes of the enclosure entrance, hall and ancestral hall maintain a high level of reconstruction completeness and texture reduction. Among them, the hall area has the most stable digital restoration effect due to clear component layers and uniform light distribution. The entrance area fluctuates slightly due to external occlusion, but is still within an acceptable range as a whole.

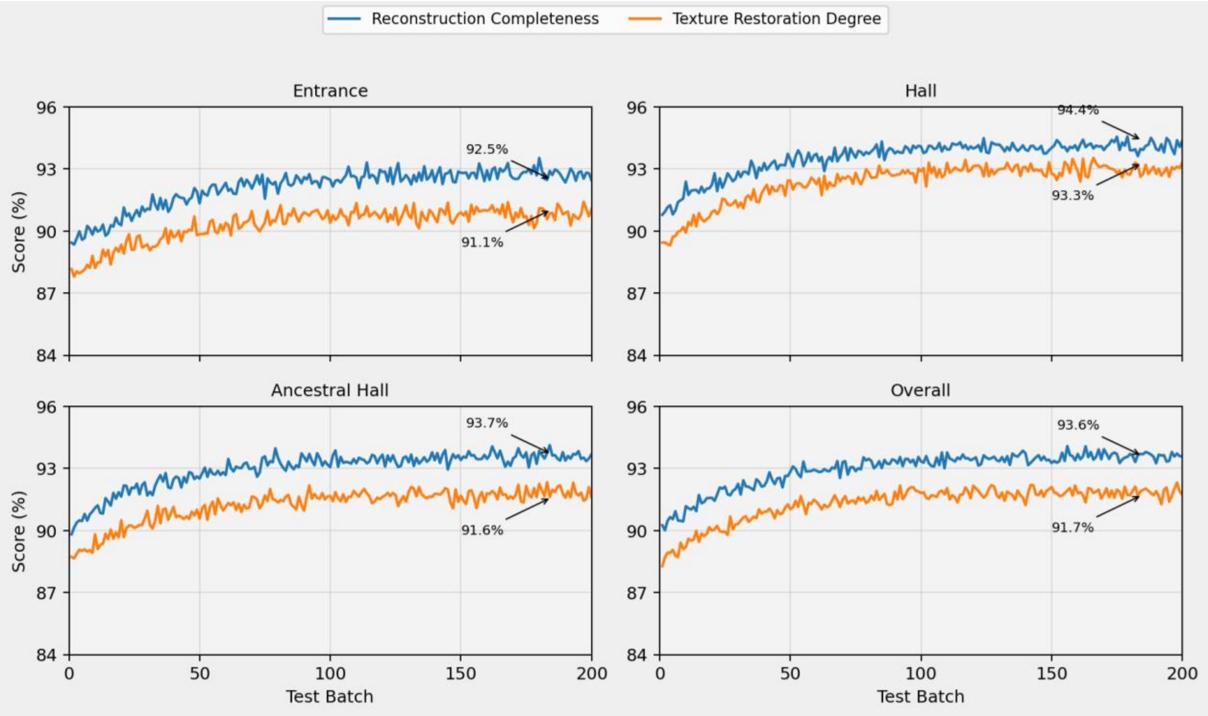

Figure 2: Comparison of reconstruction completeness rate and texture reduction of the core scene of Hakka walled houses in Henan Province

Historical information restoration is not equivalent to visual reproduction, but to write architectural components, family information, ritual functions and scene memories into digital structures together. After component-level modeling, the platform maps gatehouse, patio, beam frame, shrine, artifact and inscription nodes with text archives, dialect interpretation and activity records, so that the single scene browsing is further extended to cultural knowledge calling. The test results show that the semantic hit rate of ancestral temple nodes reaches 94.1%, the knowledge association rate of object nodes reaches 91.4%, and the time mapping rate of active nodes reaches 90.7%. This result shows that the system can not only recover the "visible" architectural outline, but also reconstruct the "interpretable" historical level. As shown in Fig. 3, the three types of information, family memory, spatial function and folk custom activity, form an obvious hierarchical distribution after mapping. The spatial function information is the most stable, and the folk custom activity information fluctuates slightly, but the overall correlation trend is clear, indicating that the platform still maintains a good organizational ability when dealing with dynamic cultural content.

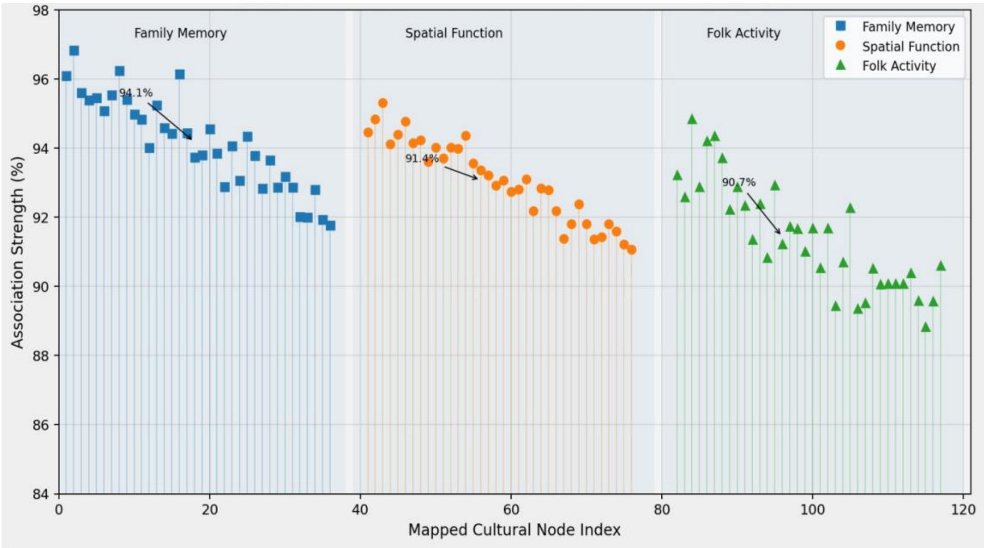

Figure 3: Distribution of association strength of various cultural nodes after historical information mapping

From the platform operation results, the effect of digital protection is also reflected in the continuity and call efficiency of the access process. The system was tested on mobile terminals, web terminals and immersive terminals in parallel, and the average response delay was 1.5 s, 1.2 s and 1.8 s, respectively. The content call consistency rate reached 92.3%, and the smoothness of node switching reached 90.8%. The guide tips, dialect explanation and historical images collection on the path from the entrance of the wai-house to the ancestral hall can be completed in a sequence in a single visit without obvious breakage. For Hakka cultural heritage, this ability of continuous use means that digital protection is no longer static retention, but can support a composite use scenario of display, research and dissemination. As shown in Fig. 4, the three types of terminals have little difference in content call success rate and feedback stability. The web terminal performs better in knowledge retrieval, the immersive terminal has advantages in spatial perception, and the mobile terminal maintains high efficiency in path guidance and instant access.

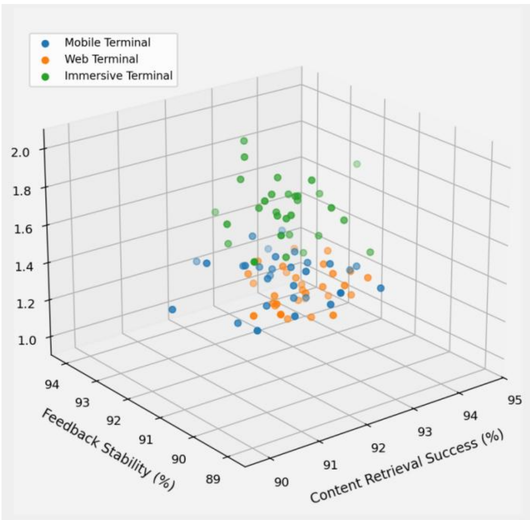

Figure 4: Performance of different terminals in content call success rate and feedback stability

The comprehensive analysis shows that the digital protection process of Hakka cultural heritage in Henan province has formed a continuous result link from geometric reconstruction, texture restoration to knowledge mapping and terminal call. This method enables the spatial details, historical information and cultural semantics of the enclosure buildings to be saved in a unified platform, and provides a reliable data basis for subsequent intelligent display, state monitoring and regional dissemination. This result shows that the digital protection enabled by science and technology not only enhances the retention accuracy of historical information, but also makes the display mode of Hakka cultural heritage closer to the application form of continuous updating and multi-terminal sharing.

4.2 Analysis of wisdom development path of Hakka cultural heritage in Henan Province

The intelligent development of Hakka cultural heritage in Henan province is not to add a number of service entrances after digital protection, but to gradually transform scene reconstruction, knowledge organization, terminal collaboration and platform feedback into sustainable operation service links on the premise of unified data base. After the completion of digital retention, the architecture of the wai-house, the ancestral hall space, the object node, the genealogy data and the folk custom activities have already had the structured expression ability. Therefore, the judgment focus of the development path is no longer limited to the single display effect, but falls on the efficiency of resource call, the stability of cross-end collaboration and the ability of service extension. Platform tests show that the success rate of knowledge retrieval reaches 93.2%, the cross-end call consistency rate reaches 91.7%, and the completion rate of scene update reaches 90.9%, indicating that Hakka cultural heritage has been able to further move from digital display to platform services. As shown in Fig. 5, the three indicators of resource integration, service responsiveness and propagation expansion keep synchronous growth in the iterative process, and the service responsiveness is the most obvious improvement, indicating that the unified scheduling mechanism has a direct role in promoting the development of intelligence.

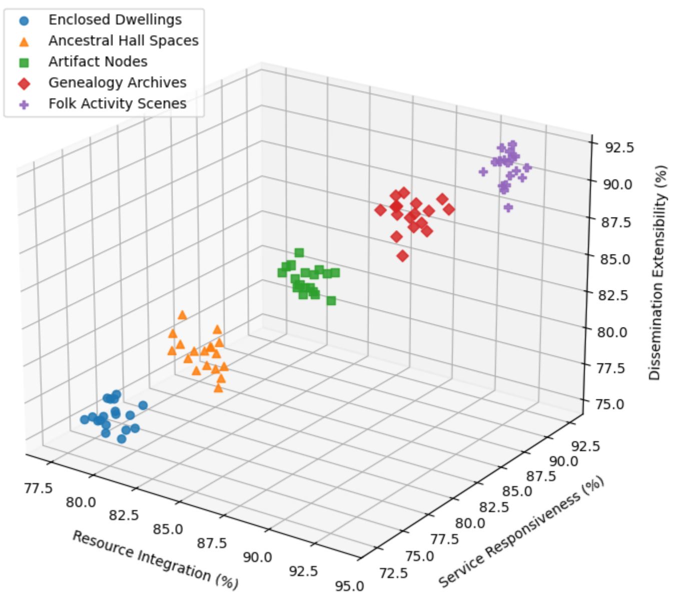

Figure 5: Changing trend of core indicators of wisdom development of Hakka cultural heritage in Henan Province

In order to more clearly compare the differences of different technology paths in the platform operation structure, the relevant results are shown in Table IV.

Table 4: Comparison of capability structures for different technology paths

Path Type	Semantic Coverage Completeness / %	Terminal Access Stability / %	User Task Completion Rate / %	Data Synchronization Error / %
Rule-based Path	84.7	86.1	83.9	6.8
Single-modal Presentation Path	87.9	88.4	86.5	5.9
Multi-source Collaborative Path	92.6	91.8	90.7	3.4

It can be seen from Table 4 that the multi-source collaborative path performs better in the three dimensions of semantic coverage completeness rate, terminal access stability rate and user task completion rate, while the data synchronization error is kept at a low level. This shows that the formation of intelligent development path does not depend on a single display ability, but is built on the common support of multi-source information unified coding, cross-terminal stable access and platform data synchronization control. Although the implementation of rule-driven path is straightforward, the semantic coverage is limited and the data synchronization error is relatively high. The single-modal display path improves the content presentation in the access process, but there are still clear boundaries in multi-type resource organization and terminal collaboration. The multi-source collaborative path can integrate the building, historical data, object nodes and activity information into the unified service link, so that the platform operation is closer to the application form of continuous update and multi-terminal sharing.

To further analyze the contribution of each module to the overall path, the ablation results are shown in Table 5.

Table 5: Ablation results of platform modules

Model Configuration	Knowledge Retrieval Success Rate (%)	Cross-Terminal Invocation Consistency (%)	Scene Update Completion Rate (%)	Average Response Delay (s)
Full Platform	93.2	91.7	90.9	1.6
Without Knowledge Mapping Module	89.4	88.2	87.6	1.8
Without Terminal Collaboration Module	90.1	85.7	88.4	2.1
Without Feedback Update Module	91.3	89.1	84.8	1.9

Table 5 shows that the knowledge mapping module has the most direct impact on retrieval ability, the terminal collaboration module has the most obvious impact on cross-end consistency, and the feedback update module determines the stability degree of the scene update completion rate. Together, the three types of modules constitute the core fulcrum in the path of smart development. For Hakka cultural heritage in Henan province, the formation of the development path is not simply to increase the application interface, but to maintain the expresability of resources through unified modeling, to enhance the content interpretability through knowledge mapping, to improve the service accessibility through terminal collaboration, and to maintain the sustainable operation of the platform through feedback update. On the whole, the intelligent development empowered by science and technology has transitioned from the stage of digital preservation to the stage of service organization. This path not only strengthens the computer expression ability of cultural resources, but also enhances the continuous operation level of Hakka cultural heritage in Henan Province in the process of display, dissemination and sharing. And it provides more stable technical support for subsequent regional linkage communication, platform expansion and fine management.

5 Discussion

With the continuous entry of Internet of things perception, virtual interaction and intelligent recognition, cultural heritage protection has gradually shifted from static recording to dynamic perception, process analysis and service linkage. Aiming at the digital protection practice of Hakka cultural heritage in Henan province, the multi-source collection, three-dimensional reconstruction, knowledge mapping and terminal collaborative link constructed in the previous section have shown that computer technology can not only improve the degree of spatial information restoration, but also enhance the organizational efficiency and communication continuity of cultural content. From the platform operation results, the unified data base has an obvious support role for scene call, terminal access, status monitoring and feedback update, and the association expression of the enclosure architecture, ancestral hall space, object node, family tree data and folk custom activities can be completed in the same service link. Therefore, digital protection is no longer a single point of display, but a composite structure oriented to display, research, dissemination and management. At the same time, the formation of intelligent development path also shows that multi-source collaboration is better than single module stacking, knowledge mapping enhances content interpretability, terminal collaboration improves service accessibility, and feedback update maintains the continuity of platform operation. Combined with the results of this paper, it can be seen that the Hakka cultural heritage in Henan Province has the technical foundation from digital preservation to continuous service, and the subsequent display and call, environmental monitoring and regional communication can maintain collaborative operation in a unified platform, and further support the fine management and dynamic sharing of cultural resources. With the computer modeling as the core, the protection logic, display logic and service logic of Hakka cultural heritage can be uniformly expressed in the same data structure.

6 Conclusions

Focusing on the needs of Hakka cultural heritage protection and intelligent development in Henan province, this paper constructs a computing framework consisting of multi-source data collection, digital modeling, virtual interaction, knowledge mapping, terminal collaboration and feedback update, so that the digital retention, semantic organization and service call of wai-house buildings, ancestral hall space, artifact nodes, family tree data and folk custom activities can be completed in a unified platform. The results show that the framework can maintain high consistency between spatial restoration, content retrieval, cross-end access and scene update, indicating that the protection of Hakka cultural heritage empowered by science and technology has the implementation foundation from static display to continuous service. The limitations of this paper are mainly reflected in the fact that the quality of heterogeneous data is still affected by acquisition conditions, the alignment accuracy between dialect audio, active images and historical texts still fluctuates, the terminal load balancing in complex scenes still needs to be further refined, the detail loss of some component textures still exists under low illumination acquisition conditions, and the knowledge mapping results still depend on manual verification to a certain extent. The follow-up research can focus on lightweight deployment, adaptive rendering, cross-regional knowledge interconnection and dynamic semantic update, so that the platform can maintain stable operation in a larger scale cultural space, and further enhance the access efficiency of mobile terminals, the collaboration ability of edge nodes and the incremental update ability of multi-modal data. At the same time, it can combine spatio-temporal graph reasoning and standardized interface construction. It improves the data reuse efficiency and platform compatibility level between different heritage types, continuously enhances the continuity and sharing level of historical information expression, and provides more stable spatial support for subsequent regional platform linkage, resource hierarchical scheduling and knowledge service expansion.

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References

[1] Albertini N, Baldini J, Dal Pino A, et al. PROTEUS: an immersive tool for exploring the world of cultural heritage across space and time scales[J]. Heritage Science, 2022, 10(1): 71.

[2] Gherardini F, Sirocchi S. Systematic integration of 2D and 3D sources for the virtual reconstruction of lost heritage artefacts: the equestrian monument of Francesco III d’Este (1774–1796, Modena, Italy)[J]. Heritage Science, 2022, 10(1): 96.

[3] Foryś P, Sitnik R, Markiewicz J, et al. Fast adaptive multimodal feature registration (FAMFR): an effective high-resolution point clouds registration workflow for cultural heritage interiors[J]. Heritage Science, 2023, 11(1): 1-23.

[4] Yang S, Hou M, Li S. Three-dimensional point cloud semantic segmentation for cultural heritage: a comprehensive review[J]. Remote Sensing, 2023, 15(3): 548.

[5] Abergel V, Manuel A, Pamart A, et al. Aïoli: A reality-based 3D annotation cloud platform for the collaborative documentation of cultural heritage artefacts[J]. Digital Applications in Archaeology and Cultural Heritage, 2023, 30: e00285.

[6] Wang Y, Wang S, Pan Y, et al. Immersive virtual reality and computer vision for heritage: visual evaluation and perception of the industrial heritage sites along the Yunnan–Vietnam railway (Yunnan section)[J]. Heritage Science, 2024, 12(1): 1-15.

[7] Chen Y, Wang X, Le B, et al. Why people use augmented reality in heritage museums: a socio-technical perspective[J]. Heritage Science, 2024, 12(1): 1-19.

[8] Wang Y, Zhou P, Geng G, et al. Enhancing point cloud registration with transformer:

Cultural heritage protection of the Terracotta Warriors[J]. Heritage Science, 2024, 12(1): 1-13.

[9] Tian F, Li K, Huang X, et al. An empirical study of virtual museum based on dual-mode mixed visualization: the Sanxingdui bronzes[J]. Heritage Science, 2024, 12(1): 1-14.

[10] Hidalgo-Sánchez F M, Merino-del-Río R, Mascort-Albea E J, et al. Digital reactivation of territories through geospatial cultural itineraries: the VIDA-HTL web application[J]. Heritage Science, 2024, 12(1): 1-27.

[11] Liu B, Wu C, Xu W, et al. Emerging trends in GIS application on cultural heritage conservation: A review[J]. Heritage Science, 2024, 12(1): 1-14.

[12] Mu P Y, Fraser S E, Peng M. Simulating urban evolution by H-GIS and H-BIM: a temporal and spatial study of Pingjiang map[J]. Heritage Science, 2024, 12(1): 392.

[13] Mishra M, Lourenço P B. Artificial intelligence-assisted visual inspection for cultural heritage: State-of-the-art review[J]. Journal of Cultural Heritage, 2024, 66: 536-550.

[14] Intrigila C, Giannetti I, Eramo E, et al. HBIM for conservation and valorization of structural heritage: The Stylite Tower at Umm ar-Rasas, Jordan[J]. Journal of Cultural Heritage, 2024, 70: 397-407.

[15] Lombardi M, Rizzi D. Semantic modelling and HBIM: A new multidisciplinary workflow for archaeological heritage[J]. Digital Applications in Archaeology and Cultural Heritage, 2024, 32: e00322.

[16] Buldo M, Agustín-Hernández L, Verdoscia C. Semantic Enrichment of architectural heritage point clouds using artificial intelligence: the Palacio de Sástago in Zaragoza, Spain[J]. Heritage, 2024, 7(12): 6938-6965.

[17] Li W, Pan J, Hasegawa K, et al. Missing region completion network for large-scale laser-scanned point clouds: application to transparent visualization of cultural heritage[J]. Remote Sensing, 2024, 16(15): 2758.

[18] Crisan A, Pepe M, Costantino D, et al. From 3D point cloud to an intelligent model set for cultural heritage conservation[J]. Heritage, 2024, 7(3): 1419-1437.

[19] Zhang J, Ren T. A conceptual model for ancient Chinese ceramics based on metadata and ontology: a case study of collections in the Nankai University Museum[J]. Journal of Cultural Heritage, 2024, 66: 20-36.

[20] Battini C, Ferretti U, De Angelis G, et al. Automatic generation of synthetic heritage point clouds: Analysis and segmentation based on shape grammar for historical vaults[J]. Journal of Cultural Heritage, 2024, 66: 37-47.