Research on University Spatial Service System Design Based on UE5 and Digital Twin Technology

Jiacheng Guo#, Yongjia Qian#, Jun Zhou*, Xuanyan Guo, Yinbo Wo, Can Song, Kangning Xia*
Jiangsu Normal University KeWen College, Xuzhou, Jiangsu, China
**Corresponding Author*
#These two authors contributed equally to this work

Abstract: With rapid iteration of digital twin and real-time 3D rendering technologies, smart campus construction is evolving from basic 2D information display to immersive service-oriented digital scenes. Traditional campus platforms based on 2D maps, static web pages and manual consultation suffer from poor spatial visualization, fragmented data and insufficient interactivity, making it difficult for teachers, students and visitors to locate facilities and complete campus services efficiently. To address these limitations, this paper proposes a university spatial service system built on Unreal Engine 5 (UE5) and digital twin. A five-layer decoupled architecture is adopted to realize bidirectional data synchronization between physical campus entities and administrative services, alongside four core modules: immersive roaming, indoor-outdoor integrated navigation, virtual-real information retrieval and one-stop service guidance. The system integrates the UE5 Navigation Mesh and MySQL database, connecting the 3D scene models with the campus business data to form a closed-loop service workflow of "inquiry-guidance-navigation". The prototype is used for comparative quantitative experiments, which can reduce the information query latency by 43.75% and the path calculation cost by 48.89% compared with the conventional 2D platform, while keeping a steady frame rate of 58-62 FPS on a common PC. This research proposes a comprehensive engineering framework for digital twin smart campus construction and extensible technical support for subsequent campus service optimization.

Keywords: Digital Twin; Unreal Engine 5; Smart Campus; 3D Spatial Service; Navigation Mesh; Virtual-Real Data Linkage

1. Research Background and Related Work

1.1 Research Background

The construction of modern university campuses regards digital transformation as an important development direction. As the scale of campus construction is continuously expanding and the demand for student administrative services is becoming more diverse, the traditional service modes which rely on two-dimensional electronic maps, static official websites and offline manual consultation cannot meet the needs of daily use. In real campus cases, freshmen, off-campus visitors and even in-service teachers often encounter pain points such as difficulty in finding office spaces, ambiguity in administrative procedures, and repeated empty visits to offices due to unknown teachers' schedules.

Digital twin technology constructs a one-to-one virtual mapping of physical entities through geometric modeling and real-time data synchronization, integrating spatial geometric data, business attribute data, and human-computer interaction logic [1]. In recent years, it has been widely applied in smart cities, intelligent manufacturing, and building operation fields, and has gradually been introduced into campus digital construction. However, most existing digital twin campus platforms only focus on static three-dimensional display and fixed-point roaming, lacking deep integration with real campus administrative affairs, teacher information, and on-duty state data. The separation of spatial display and practical services leads to low utilization value of such systems.

In addition, most traditional campus navigation tools only support outdoor two-dimensional route planning, without indoor multi-floor pathfinding capability, and cannot visually display the spatial relationship between classrooms, offices, and service windows. Aiming at the above defects, this paper takes Jiangsu Normal University KeWen College as the research object, combines the UE5 high-fidelity real-time rendering engine, Blender lightweight modeling tool, and MySQL database, develops an integrated university spatial service system integrating modeling, roaming, intelligent navigation, and affair guidance, and completes quantitative testing and performance optimization of the prototype system.

1.2 Domestic and Overseas Research Status

1.2.1 Foreign research status

Foreign universities started early on digital twin and 3D campus visualization research. Many comprehensive universities have built campus virtual roaming platforms based on the UE4 and UE5 engines, combined with GIS spatial data, to realize outdoor large-scale scene browsing and simple path marking. European and American scholars focus on the combination of virtual campus and AR/VR immersive experience and realize remote campus online reception function [2].

Nevertheless, foreign research still has obvious deficiencies:

High construction cost, mostly deployed in research universities with sufficient R&D funds, lacking low-cost lightweight schemes suitable for independent colleges;

Function homogenization is serious, only retaining spatial display, without docking local university administrative procedures, teacher attendance, and other personalized service data;

The built-in Navigation Mesh pathfinding module only adapts to single-layer open outdoor areas, and the pathfinding stability declines sharply in complex multi-floor indoor environments with stairs and partition walls [3].

1.2.2 Domestic research status

Domestic scholars have carried out a large number of studies on digital twin smart campuses in recent years.Relevant literature can be divided into three categories: campus 3D modeling optimization research, panoramic virtual roaming system development, and campus information management platform design [4].

Most existing achievements have the following three prominent limitations:

Separation of space and service: 3D models only store appearance texture data, unable to bind teacher information, office service scope, and dynamic on-duty status;

Weak indoor navigation capability: Most systems abandon multi-floor automatic pathfinding and only rely on manual text prompts to mark locations.

Lack of service closed loop: Navigation function and administrative affair handling are independent modules; users need to switch multiple platforms to complete the whole process of "check materials → find departments → go through procedures".

1.2.3 Research gap and innovation orientation

Through the sorting of domestic and foreign literature, it can be seen that there is a lack of a set of low-cost, fully functional integrated spatial service systems that integrate indoor and outdoor navigation, teacher state visualization, and one-stop affair guidance.

This paper makes targeted improvements:

Build a five-layer decoupled architecture to separate data collection, modeling, rendering, and business logic, which is convenient for subsequent module expansion;

Optimize navigation mesh baking logic to realize automatic cross-floor pathfinding for indoor and outdoor scenes;

Establish three types of association databases to realize real-time linkage between 3D models and dynamic campus service data;

Form a complete service closed-loop of "inquiry → procedure display → automatic navigation" for student administrative affairs.

1.3 Main Innovations of This Paper

Concept Innovation:

Propose the "space-service integration" design idea, transform the digital twin campus from a simple visual display carrier to a practical service platform, break the single display limitation of traditional virtual campus systems;

Architecture Innovation:

Design a five-layer hierarchical decoupling system framework including the data acquisition layer, digital model layer, interaction engine layer, service application layer, and user layer, which has strong scalability and convenient module iterative upgrade;

Functional Innovation:

Realize indoor and outdoor integrated automatic navigation based on optimized UE5 Navigation Mesh, and add a teacher-on-duty state real-time visualization module to effectively solve the problem of students' empty visits;

Engineering Innovation:

Adopt Blender lightweight modeling combined with LOD hierarchical rendering strategy to reduce model resource occupation by 32%, ensuring smooth operation on ordinary civilian computers; establish a three-category relational database to realize one-click linkage between 3D model click events and business information;

Experimental Innovation:

Set the traditional two-dimensional campus map system as the control group, carry out quantitative comparison experiments on query delay, pathfinding speed, and frame rate, and intuitively verify the performance advantages of the proposed system.

2. System Overall Design and Digital Twin Model Construction

2.1 Five-Layer Decoupled System

Architecture:

The system adopts a bottom-up layered design; each layer completes independent functions and realizes standardized data interaction through unified interfaces.

Data Acquisition Layer:

Collect multi-source physical campus data: obtain building size, indoor layout, and corridor structure through field measurement and on-site shooting; sort out text data such as teacher information, department functions, and student administrative procedures, and complete data desensitization and standardized sorting to provide raw data support for upper modeling and database construction.

Digital Model Layer:

Take Blender as the modeling tool to complete the initial reconstruction of campus buildings and indoor scenes, carry out polygon reduction, texture compression and LOD hierarchical optimization processing for high-precision rough models, and convert lightweight assets into UE5-compatible format to complete scene splicing and environmental rendering configuration.

Interaction Engine Layer:

Take Unreal Engine 5 as the core carrier, rely on Nanite virtual geometry and Lumen global illumination to realize high-fidelity scene rendering; integrate the improved Navigation Mesh pathfinding module to complete automatic obstacle avoidance and cross-floor route calculation; provide first/third-person character roaming control logic.

Service Application Layer:

Develop four core business modules: immersive virtual roaming module, indoor and outdoor intelligent navigation module, virtual-real information service module, and campus affair one-stop guidance module; build a MySQL data interaction interface to realize two-way transmission between the engine front end and background business data.

User Interaction Layer:

Provide a mouse-keyboard interactive operation interface for teachers and students, support keyword search, model click query, affair selection, one-click navigation, and other human-computer operations, and pop up standardized information panels to display spatial and business data.

2.2 Lightweight Digital Twin Campus Modeling Process

The modeling process is divided into four standardized stages to balance model fidelity and system running fluency:

To unify the technical baseline, the improved A* algorithm is adopted for path planning, LOD hierarchical optimization is used for model lightweighting, Lumen provides global illumination, and Blender serves as the primary modeling tool [5-8].

Step 1 Multi-source Data Collection:

Carry out field measurements of teaching buildings, office buildings, and public areas of KeWen College, collect front, side, and indoor detail images of all buildings with cameras and laser rangefinders, sort out floor plans, and record the coordinate range of each office, classroom, and service window to form a complete spatial data set. For business data, communicate with college administrative offices to obtain public information about faculty and routine handling procedures, and remove private sensitive information for desensitization treatment.

Step 2 Initial Three-dimensional Reconstruction and Rough Model Generation:

Import collected image data into the Blender photogrammetry plug-in to automatically generate dense point clouds and surface mesh rough models. The initial rough models have a large number of redundant triangular surfaces, repeated high-resolution textures, and broken wall structures that cannot be directly imported into the engine for real-time operation.

Step 3 Lightweight Model Optimization Strategy:

Four core optimization schemes are adopted to reduce hardware rendering pressure:

Polygon simplification: Delete invisible internal surfaces and repeated decorative components of buildings, and control the total surface number of single building models within a reasonable range;

Texture compression: Classify scene objects, assign high-precision textures to interactive key areas, and compress the resolution of distant green plants and auxiliary buildings;

Structural repair: Repair the broken models of stairs, doors, and windows to ensure the connectivity of indoor walkable areas for navigation grid baking;

LOD hierarchical rendering: Set multiple levels of detail for each model. High-precision models are loaded when the camera is close, and low-precision simplified models are automatically switched when the viewing distance is far away to reduce GPU load.

To quantify the optimization effect, the model resource optimization rate is defined as:

$$\eta_{model}=\frac{M_{raw}-M_{opt}}{M_{raw}}\times100\% \quad (1)$$

where M_{raw} denotes the total resource consumption of the raw model (including triangle count and texture memory), and M_{opt} denotes the resource consumption after optimization.

Step 4 UE Scene Integration and Navigation Baking:

Import all optimized model resources into UE5, complete material matching, global light source layout, and shadow parameter adjustment; divide indoor and outdoor walkable areas, set wall, flower bed, and other static obstacle collision bodies, bake Navigation Mesh navigation grid covering all floors, and write blueprint scripts to link coordinate data with the background database.

After the above process, the overall resource occupation of the campus scene model is reduced by 32% compared with the original unoptimized model, and it can run stably on ordinary laptops equipped with GTX1660 and above graphics cards.

2.3 Spatial-Service Data Association Mechanism

Unique identifiers are assigned to each spatial object in the 3D scene, and the identifier is associated with three core MySQL data tables to realize automatic data calling after clicking the model. The unique identifier formula of a spatial object is defined as:

$$ID_i=(B_i,F_i,R_i) \quad (2)$$

Where B_i represents building serial number, F_i represents floor number, R_i represents room number.

Whenever the user clicks to select any building or office model in the scene, the engine will record the object ID and send a query query to the background database, and the database will return the corresponding matched teacher information, office functions and on-duty state data to the front-end pop-up panel. Figure 1 shows the data interaction mechanism between spatial objects and MySQL database.

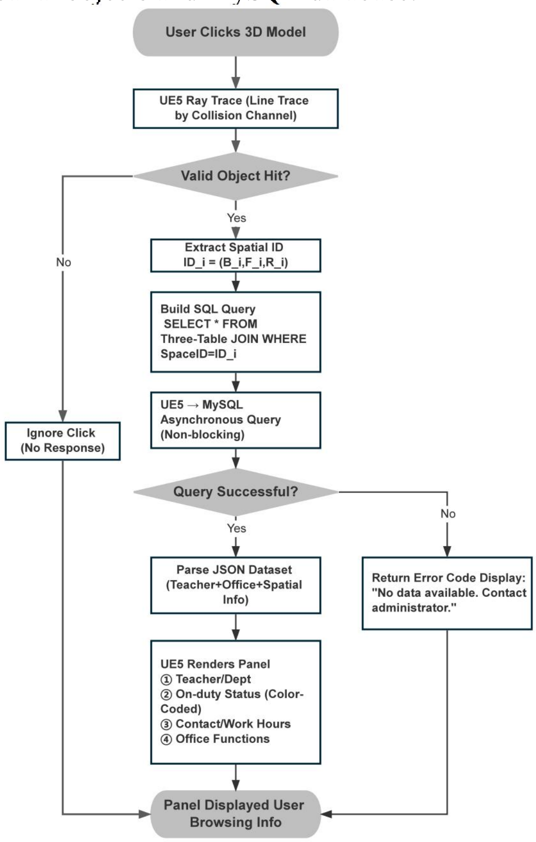

Figure 1. Flowchart of Spatial Object and MySQL Database Data Interaction Mechanism

3. Development of Core Functional Modules

3.1 Immersive Virtual Roaming Module

The module abandons the fixed-angle panoramic mode of traditional campus platforms and provides two controllable roaming perspectives to meet different usage scenarios:

First-person View Roaming Users can walk by pressing WASD keys and change the viewing angle by moving the mouse, which mimics real walking on the campus. It allows for close observation of classrooms and offices, making it easy for students to locate specific spots.

Third-person Virtual Character Roaming Built-in controllable humanoid avatar; users can see the surrounding campus layout from an external perspective, suitable for freshman online campus tours and external visitor demonstration activities.

To maintain stable rendering performance during roaming, the system adopts a performance model that relates frame rate to scene complexity:

$$FPS=\frac{K}{N_{triangles}\times C_{complexity}} \quad (3)$$

where FPS denotes the real-time rendering frame rate, $N_{triangles}$ is the total triangle count of the scene, $C_{complexity}$ is the material and lighting complexity coefficient, and K is a hardware performance constant. This model guides the LOD switching strategy: when FPS falls below 55, the system automatically reduces the triangle budget of distant models to maintain the target frame rate of 58–62 FPS.

In addition, interactive collision components are added to all functional rooms. After clicking the model, the system automatically calls background data and pops up information panels including department introductions, office hours, and contact information, realizing the integration of scene display and information storage.

3.2 Indoor and Outdoor Integrated Intelligent Navigation Module

Based on the baked Navigation Mesh grid, the system realizes full-automatic pathfinding covering outdoor roads and multi-layer indoor buildings, and solves the pain point of difficult indoor positioning of traditional campus navigation tools [9].

Spatial coordinate mapping mechanism

All offices, classrooms, and service windows correspond to three-dimensional coordinate data

$$P_i=(x_i,y_i,z_i) \quad (4)$$

In the database, where x, y are horizontal plane coordinates, and z represents floor height. After the user searches for the target name, the system quickly matches the corresponding coordinate point as the navigation end point.

The execution flow of indoor and outdoor integrated intelligent navigation is illustrated in Figure 2.

Stage 1: Target input and database matching – The user enters a room number, teacher name, or transaction type. The system parses keywords against the Teacher Information Table and Spatial Coordinate Table, retrieving the target coordinate $P_{target}=(x_t,y_t,z_t)$. If the target is not found, the system displays a user-friendly error message.

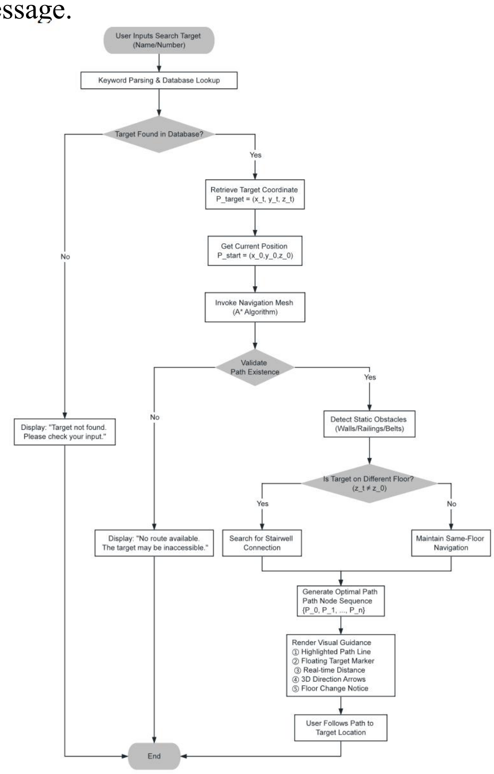

Figure 2. Flowchart of Indoor and Outdoor Integrated Intelligent Navigation Execution

Stage 2: Path computation via navigation mesh – The system retrieves the user's current position $P_{start}=(x_0,y_0,z_0)$ and invokes the UE5 Navigation Mesh A* algorithm [9]. The optimal path minimizes the total travel distance:

$$D_{total}=\min\sum_{i=1}^{n}\|P_i-P_{i-1}\| \quad (5)$$

where $\{P_0,P_1,\ldots,P_n\}$ is the ordered sequence of navigation nodes, with $P_0=P_{target}$ and $P_n=P_{target}$. The Euclidean distance between adjacent nodes is:

$$\|P_i-P_{i-1}\|=\sqrt{(x_i-x_{i-1})^2+(y_i-y_{i-1})^2+(z_i-z_{i-1})^2} \quad (6)$$

Stage 3: Obstacle detection and cross-floor validation – The Navigation Mesh identifies static obstacles (walls, railings, green belts, flower beds, and fixed furniture). There is a dedicated judgment for height discrepancy between z_t and z_0. Once unequal, the system matches the nearest stair node and adds climbing sections to the planned path. If no feasible route can be calculated in the end, a system notification will be triggered accordingly.

Stage 4: Visual guidance rendering – Five types of guidance cues are rendered by the system: a continuous highlighted path line, a floating 3D target marker, real-time remaining distance display, 3D directional arrows at decision points and explicit floor transition notifications.

Step 5: Live validation and arrival – The system keeps track of the user's position in real-time, as the user navigates. Any deviation will automatically recalculate a new route. Navigation ends when the spatial distance between the current position and the target point fulfills the following constraint:

$$\|P_{current}\text{-}P_{target}\|<\varepsilon \quad (7)$$

where ε represents the arrival tolerance threshold for navigation termination. Referring to the Euclidean distance model in Equation (6), this constraint determines whether the user reaches the target space, and ε is set to 0.5 in this system.

Multi-dimensional visual guidance

In the navigation state, the system displays four auxiliary prompts at the same time: continuous highlighted path lines, floating target markers, real-time remaining distance, and 3D directional arrows, which greatly reduce the user's spatial identification cost compared with pure text navigation.

3.3 Virtual-Real Integrated Spatial Information Service Module

The module is the core link to realize the transformation from "scene display" to "campus service". Three types of MySQL data tables are designed to store classified campus business data [10].

The Teacher Information Table (Table 1), Office Function Table (Table 2), and Spatial Coordinate Table (Table 3) store the core business data.

To support keyword-based search functionality, the system employs a relevance scoring algorithm. For a user query Q = consisting of m keywords, the matching score for a database record R is:

$$\mathrm{Score(Q,R)}=\sum_{j=1}^{m} w_j \cdot \delta(t_j, R) \quad (8)$$

The symbol w_j stands for the weight of keyword t_j. This weight value is decided by two factors: the keyword's semantic weight and its distinguishing capacity. $\delta(t_j,R)$ acts as a binary matching indicator function. It equals 1 when t_j shows up within any indexed field belonging to record **R**, while the value turns to 0 if no such match exists. After computing the Score of every candidate record, the system ranks these records from high Score to low and displays the highest-ranked entries to users.

Table 1. Teacher Information Table

Field Name	Data Type	Description
TeacherID	VARCHAR	Unique identification number
Name	VARCHAR	Full name of teacher
Department	VARCHAR	Affiliated school/department
OfficePos	VARCHAR	Specific office floor & room
WorkStatus	INT	0=off duty, 1=in class, 2=in a meeting, 3=on duty
Contact	VARCHAR	Contact information
WorkTime	VARCHAR	Daily office hours

Table 2. Office Function Table

Field Name	Data Type	Description
OfficeID	VARCHAR	Unique office number
DeptName	VARCHAR	Functional department
ServiceScope	TEXT	Administrative business responsible
StaffNum	INT	Number of staff
Tel	VARCHAR	Service contact number

Table 3. Spatial Coordinate Table

Field Name	Data Type	Description
SpaceID	VARCHAR	Spatial object unique ID
Building	VARCHAR	Building name
Floor	INT	Floor number
Coordinate	VARCHAR	X, Y, Z three-dimensional coordinates
NavLink	TEXT	Connected navigation node path

Teacher On-Duty State Visualization Function

Teachers open the background management terminal to update their real-time status (in class, meeting, on duty, off duty) in one click, and the data is synchronized to the 3D scene in real time. When students click the corresponding office model, they can check the teacher's current state, avoiding unnecessary empty trips to office, and achieving consultation efficiency.

3.4 One-Stop Campus Affair Guidance Module

In dealing with general student administrative businesses such as student status certificate application, transcript printing and make-up exam registration, the module establishes a full-process closed-loop service with procedure display and automatic navigation.

A closed-loop service flow of one-stop campus affairs is shown in Figure 3.

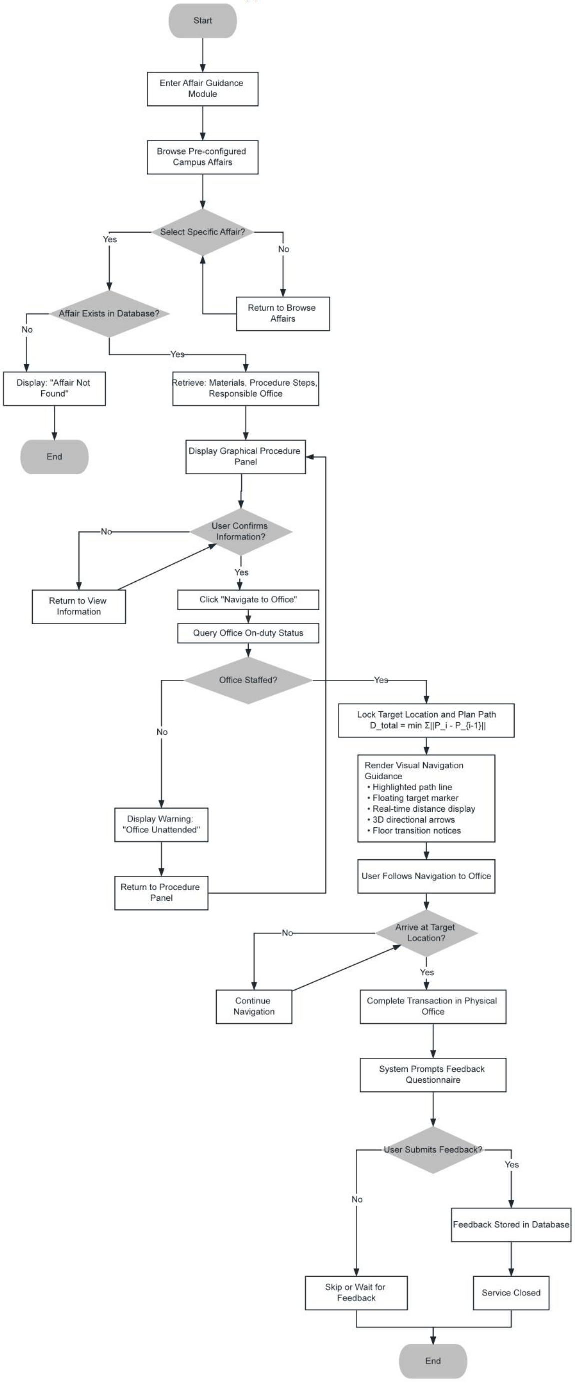

Figure 3. Flowchart of One-Stop Campus Affair Full Service Closed-Loop

Analyze more than 10 types of high-frequency campus affairs, collect related handling materials, handling steps and related departments, store them in the database;

Use graphical interactive panel to display the procedures, rather than single text paragraph, so the students can quickly understand the preparation work before proceeding with the affairs.

After confirming the business service type, the system will automatically lock the corresponding office coordinate point and jump to the navigation module with one click to form a complete life service chain of “check the information, understand the procedure, navigate to the location”.

4. System Implementation and Multi-dimensional Quantitative Comparative Experiments

4.1 System Development Environment

The system hardware and software environment is described in Table 4.

Table 4. System Hardware & Software Environment

Category	Specific Configuration
Operating System	Windows 11 Professional
Render Engine	Unreal Engine 5.2
Modeling Software	Blender 3.4
Database	MySQL 8.0
UI Design Tool	Figma
Development Language	C++, UE5 Visual Blueprint
Test Hardware	Intel i5 CPU, 16GB RAM, GTX 1660 Graphics Card

4.2 Full Functional Verification Test

All four core modules are tested item by item with standardized test cases, and the test results are shown in Table 5.

Table 5. Functional Test Results

Test Module	Test Content	Test Result
Virtual Roaming	First- and third-person free roaming, model click query	Passed
Intelligent Navigation	Outdoor pathfinding, cross-floor indoor navigation, and obstacle avoidance	Passed
Spatial Information Service	Teacher status real-time synchronization, office information query	Passed
Campus Affair Guidance	Procedure display, one-click navigation linkage, and feedback submission	Passed

All preset functions operate normally without logic crashes or data loss, meeting daily campus service requirements.

4.3 Quantitative Performance Comparative Experiment

On the basis of taking the conventional

two-dimensional campus map system as the control group, conduct quantitative testing on the unified test platform to collect the performance indicators, as shown in Table6.

Table 6. System Performance Comparison Test Data

Evaluation Index	Traditional 2D Campus System	Proposed 3D Digital Twin System	Optimization Effect
Initial scene loading time	0.8s	2.1s	3D scene needs resource loading, acceptable delay
Average information query delay	0.32s	0.18s	Reduced by 43.75%
Average path calculation time	0.45s	0.23s	Reduced by 48.89%
Stable running frame rate	No rendering demand	58~62 FPS	Smooth operation without stalling

To quantify the performance improvement, the optimization rate is defined as:

$$\eta=\frac{T_{2D}-T_{3D}}{T_{2D}}\times 100\% \quad (9)$$

Here,T_{2D} refers to the response delay measured from classic 2D campus positioning systems, and T_{3D} represents the response performance of the 3Dnavigation framework raised in this paper. All datasets recorded in Table 6 are adopted to compute the optimization rate η. In terms of information searching delay, we get η=(0.32−0.18)/0.32×100%=43.75%; for path calculation time, η=(0.45−0.23)/0.45×100%=48.89%.

Experimental results analysis: Although the 3D system requires a little longer time for the initial loading, the speed advantage of the core functional links of information query and pathfinding is obvious, the frame rate is stable during roaming, and the overall user experience is relatively good.

4.4 Test Summary

All functional tests have been passed by the prototype system, and quantitative comparison test results demonstrate that the prototype system outperforms traditional two-dimensional platforms. The lightweight modeling strategy effectively controls hardware resource occupation, and the indoor and outdoor integrated navigation and virtual-real data linkage functions run stably, which can effectively solve the spatial service pain points of teachers and students on campus.

5. System Limitations and Future Research Prospects

5.1 Existing System Limitations

The current Navigation Mesh only identifies static obstacles such as walls and green belts, and cannot dynamically avoid temporary roadblocks and real-time crowd flow;

The prototype only supports PC terminal operation, and there is no lightweight mobile terminal adaptation scheme. Mobile access will face problems such as slow loading and inconvenient operation;

The system database only stores fixed public data and does not realize data docking with the school's educational administration, campus card, and other existing business platforms, forming independent data islands;

No concurrent pressure test is carried out. The system operation performance under the condition of more than 50 people online at the same time is unknown.

5.2 Subsequent Optimization Research Directions

Introduce a real-time crowd flow sensing module, combine a dynamic pathfinding algorithm to realize real-time obstacle avoidance navigation for temporary crowds and road barriers;

Develop WebGL lightweight web version and mobile terminal adaptation scheme, reduce model resolution for mobile end to realize anytime access via mobile phones;

Open a standardized data interface to connect school educational administration and logistics management systems, realize full campus data interconnection;

Access the large language model API to build a campus intelligent Q&A knowledge base, support natural language inquiry of office locations and business materials;

Carry out multi-user concurrent pressure tests, optimize server data scheduling logic to improve system carrying capacity under peak online conditions.

6. Conclusion

Aiming at the defects of weak visualization, isolated business data, and a single navigation function of traditional campus service platforms, this paper constructs a university spatial service system integrating digital twin technology and Unreal Engine 5. The paper completes the lightweight 1:1 reconstruction of the campus physical scene, designs a five-layer decoupling system architecture, and develops four core functional modules, including immersive roaming, indoor and outdoor integrated intelligent navigation, virtual-real information linkage, and one-stop affair guidance. A MySQL multi-category relational database is built to realize real-time association between 3D spatial models and campus dynamic business data, forming a complete closed-loop of "information inquiry–procedure guidance – three-dimensional navigation".

Functional verification and quantitative comparative experiments show that the proposed system has faster data query and path calculation speed than traditional two-dimensional campus platforms and maintains high frame rate smooth operation under ordinary computer hardware conditions. This research provides a complete set of engineering development schemes for the application of digital twin technology in smart campus construction, and the five-layer architecture and lightweight modeling process proposed in this paper can be reused by similar colleges and universities. In the follow-up work, mobile terminal adaptation, dynamic navigation algorithm optimization, and campus multi-system data interconnection will be further studied to expand the service capacity of the spatial service platform.

Acknowledgments

This paper is supported by the University-level College Students' Innovation and Entrepreneurship Training Program of Jiangsu Normal University Kewen College (No. 2026KWCX039).

References

[1] Tao F, Zhang H, Liu A, Nee A Y C. Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics, 2019, 15(4): 2405-2415.

[2] Fuller A, Fan Z, Day C, Barlow C. Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access, 2020, 8: 108952-108971.

[3] Qi Q, Tao F. Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0. IEEE Access, 2018, 6: 3585-3593.

[4] Wang S, Li X, Chen L. Real-Time 3D Visualization of Campus Digital Twin Based on Cesium and Dynamic LOD Scheduling. IEEE Access, 2024, 12: 41678-41689.

[5] Chen J, Liu Y. Time-Varying Constrained Improved A* Algorithm for Multi-Floor Indoor Path Planning. ISPRS International Journal of Geo-Information, 2023, 12(5): 198.

[6] Ge Y, Xiao X, Guo B. Hierarchical LOD Mesh Simplification for Lightweight Building Model Real-Time Rendering. Computers & Graphics, 2024, 118: 103762.

[7] Schmitt T, Weber M. Quantitative Performance Evaluation of Lumen Global Illumination for Architectural Indoor Virtual Scenes. The Visual Computer, 2023, 39(9): 4817-4832.

[8] Koutsoudis A, Pavlidis G. Photogrammetric Reconstruction and Blender-Based Optimization Workflow for Cultural Heritage Digital Twins. Journal of Cultural Heritage, 2024, 65: 97-108.

[9] Hart P E, Nilsson N J, Raphael B. A Formal Basis for the Heuristic Determination of Minimum Cost Paths. IEEE Transactions on Systems Science and Cybernetics, 1968, 4(2): 100-107.

[10] Zhang L, Yang D. Spatial Index Optimization of MySQL for Fast Retrieval of Large-Scale 3D Scene Geometric Data. Data & Knowledge Engineering, 2023, 145: 102172.

