

Immersive Evaluation and Interactive Correction System for Environment Design Assisted by Virtual Reality Technology

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ABSTRACT Conventional environmental-design evaluation based on two-dimensional drawings and static renderings has limited ability to capture spatial perception, user behavior, and interactive modification effects. This study develops a virtual-reality-assisted immersive evaluation and real-time correction system for environmental design. Design data from BIM, CAD drawings, and material textures are converted into high-fidelity interactive VR scenes through real-time rendering, LOD optimization, and physically based material representation. Eye tracking, behavioral-path recording, and multi-dimensional evaluation indicators are integrated to measure spatial layout rationality, visual comfort, and functional accessibility. The interactive correction module supports real-time adjustment of furniture layout, materials, lighting position, color temperature, and illuminance. Experimental comparisons show that the system increases design-defect identification by 43.7%, shortens the scheme iteration cycle by 63.7%, and improves user satisfaction by 30.9%. The framework provides an engineering decision-support tool for immersive design verification, spatial sensing, and interactive visualization.

INDEX TERMS virtual reality, immersive evaluation, eye tracking, spatial sensing, interactive visualization

I. INTRODUCTION

TRADITIONAL environmental design evaluation relies on static methods such as two-dimensional drawings and physical models, which often fail to account for the complex spatial morphology and anisotropic mechanical properties of industrial integrated into modern architectural structures. Integrating the material distribution and structure density of functional materials into these evaluations provides a more precise simulation of how flexible materials influence the overall structural integrity and user experience. There is a significant difference in spatial perception between designers and clients [1]. Floor plans cannot convey a true sense of scale, renderings are limited by perspective and cannot show the full view of the space, and physical models have a long production cycle and high modification costs. This evaluation method leads to design defects being discovered only during the construction phase, resulting in a large amount of rework and waste of resources. Statistics show that the additional costs incurred by the building decoration industry due to design changes account for 15% to 25% of the total investment in the project, of which more than 60% of the changes are due to the client's misunderstanding of the spatial effect. Clients find it difficult

to imagine the real spatial experience from two-dimensional drawings, and designers repeatedly modify the plan but still cannot meet the needs. Low communication efficiency has become a bottleneck problem restricting the development of the industry.

The technology of the virtual reality offers an environment design evaluation by giving users an immersing experience of walking around and feel the scale of a high-fidelity virtual environment. The paper will design an immersive assessment and interactive correction system on environmental design using VR technology, which will combine eye-tracking, behavior path tracing, and real-time rendering technologies in order to generate multi-dimensional quantitative assessment of design schemes [2,3]. The system enables the user to directly modify design elements—including furniture arrangement, lighting options, and the spatial density or material morphology of industrial components—within the virtual mode for instant feedback. This real-time integration of functional material parameters eliminates the protracted cycles of manual drawing modification and rendering typical of conventional design processes.

II. RELATED WORK

Environmental design evaluation methods have evolved from hand-drawn sketches and physical models to computer-aided design. Computer-aided design software generates static visual effects through three-dimensional modeling and rendering technology, but due to fixed perspectives and lack of interactivity, users find it difficult to obtain a real spatial experience. Building information modeling technology integrates data from the entire life cycle of design, construction, and operation and maintenance, improving collaborative work efficiency, but its visualization interface still relies on screen display and cannot provide immersive perception [4]. Traditional evaluation methods generally adopt subjective evaluation methods such as expert scoring and questionnaire surveys, lacking objective records of user behavior and physiological reactions, and the evaluation results are greatly affected by personal experience and expression ability. Physical space simulation laboratories evaluate by building physical model rooms, which can provide a real experience, but the construction cost is high and the modification flexibility is poor, making it difficult to apply to large-scale design scheme comparison.

Architectural visualization, indoor walkthroughs, and landscape displays are some of the areas that the virtual reality technology has been utilized. Commercial display systems are oriented to the effects of visual presentation, and with the high-precision modeling and ray tracing renderer technologies generate real scenes, but do not provide functional design to design evaluation, and users are passive viewers unable to actively participate. Virtual environment is adopted in education and training systems to implement spatial cognition training to enable students to learn about the relationship between architectural scale and structural relationships, however the evaluation index system is not complete and quantitative evaluation mechanism is not yet established [5,6]. Other studies have added technology of eye-tracking into the virtual worlds to understand how the users focus on space element, however, the data collection and analysis procedures are not related to implement the design-research process and are not connected in a closed loop. The interactive correction option of the current systems is expressed as the straightforward material replacement or color adjustment, and lacks the option of real-time editing of the complex elements of the space layout and the lighting parameters. The current assessment strategies primarily deal with single-dimensional indicators and do not provide an overall assessment framework that incorporates spatial layout, visual comfort, and accessibility of functions, and the outcomes of the assessment are hard to directly reflect design optimization [7,8].

III. METHODS

A. SYSTEM OVERALL ARCHITECTURE DESIGN

Design data including the BIM models, CAD drawings, and material textures are taken as inputs to the data input layer. It converts multi-source heterogeneous data into an asset pack-

age named by Unity3D by using an FBX format converter engine and texture mapping engine. The scene rendering layer develops a real-time ray tracing rendering pipeline on Unreal Engine 4.27 and LOD (Level of Detail) technology is used to dynamically scale the precision of the model so that the model can render a 2448x2448 resolution per-eye display at 90fps on the HTC Vive Pro 2 device, matching the hardware's native panel specifications to eliminate aliasing. The perception layer incorporates the Tobii eye tracker to acquire 120Hz data on the pupil coordinates, and the SteamVR Tracking 2.0 positioning camera tracks the sequence of the 6DoF head movement and controller moves the user makes. The information is sent to the evaluation and analysis unit in real time through UDP protocol [9,10]. The altered performance layer is based on PhysX 4.1 physics engine that provides furniture collusion detection. The material editor helps to make real-time changes to PBR (Physically Based Rendering). Light system has an ability to dynamically adjust the color temperature (2700K-6500K) and illuminance (100-2000 lux). Each of the modification operations initiates an incremental scene reconstruction algorithm and the latency of response is maintained to within 50ms to make sure that the user modification intentions and visual feedback are synchronized.

B. VR-BASED IMMERSIVE SCENE CONSTRUCTION MODULE

The scene construction module converts the design scheme into an interactive virtual environment. Geometric data processing uses the Simplygon mesh optimization algorithm, that reduces the triangles of the original CAD model in the mean of 2.5 million to 800,000 triangles. To ensure geometric fidelity, the simplification process is controlled to maintain a maximum Hausdorff distance of less than 0.5mm between the original and the decimated mesh. The material system includes a PBR texture library with five channels, namely, diffuse, metallic, roughness, normal, and ambient occlusion. Single texture resolution is adjusted to 2048*2048 pixel, and the video memory consumption is minimized (BC7 compression format) to half an amount compared to the one originally.

Lightmass light baking engine uses the effects of global illumination, using a photon bouncing number of 8 and a sampling density of 64 photons per square meter to create a lightmap that is 512*512 pixels. These parameters were selected to balance indirect lighting soft-shadow quality with the computational limits of the scene's texture memory. Dynamic lighting is based on deferred rendering, and it can render 12 point lights and 4 spotlights at the same time. The shadow map resolution will be 1024*1024 pixels and cascading shadow distance will be 50 meters to reach the whole picture.

The spatial audio module also includes the Steam Audio acoustic simulation engine that computes the attenuation and reflection of audio on walls, surfaces of furniture and floors on the basis of the ray tracing algorithm. Sampling rays

are adjusted to 2048 and reverberation time is automatically adjusted based on the area of the room and the error is controlled at 0.1 seconds, therefore to attain the immersive auditory setting which corresponds to the visual setting.

C. MULTI-DIMENSIONAL EVALUATION INDEX SYSTEM AND DATA COLLECTION METHODS

The evaluation index system consists of quantitative measures of three dimensions; spatial layout rationality, visual comfort, and functional accessibility. The spatial layout test is based on a heatmap algorithm to examine the distribution of user dwell time, with units of the grid being 0.5m x 0.5m, and the cumulative dwell time and the frequency of access in each unit is recorded. The system determines high-use areas and low-use areas are automatically labeled according to the dwell time of more than 30 seconds and less than 5 seconds respectively, respectively, and the ratio between high use areas and low use areas is computed to produce a space utilization report.

The Tobii Pro Nano eye tracker is used to gather visual comfort data with the recording of changes in the diameter of the pupils, the coordinates of the fixation points, as well as blink intervals with a 120Hz frequency. The system automatically determines areas with the fixation point longer than 200ms as regions of interest (ROIs), and the first fixation time, total fixation period and the number of regressions on the area is noted. In case the change in the pupil diameter is above 15 percentages or the blink rate is below 8 times a minute, the system concludes that the participant is in the visual fatigue state and documents the trigger point and the environment conditions.

The assessment of functional accessibility is conducted by tracking the user's movement trajectory with the help of the SteamVR controller, with the sampling frequency being 90Hz. The system captures the entire 3D coordinates sequence and computes the ratio of deviation between the actual walking path and the shortest path on the theory. At the same time, angular velocity of head rotation is measured. To distinguish between active exploration and spatial confusion, an event is identified as pathfinding difficulty only when the angular velocity exceeds 180 degrees/s and is accompanied by a deviation from the logical path exceeding 45 degrees for more than 3 seconds, serving as a composite metric for user struggle. This is automatically correlated with visual blockers and absent spatial cues in that place by the system and presents a list of guidance optimization hints.

D. REAL-TIME INTERACTIVE CORRECTION MECHANISM AND RENDERING FEEDBACK

Upon a grab operation caused by the user, the raycasting algorithm identifies the boundary of the bounding box of the colliding object, creates a mapping relationship between the coordinate system of this object and the world coordinate system, and assists in furniture translation along the XYZ axis in 0.1-meter steps, and rotation accuracy in 5-degree

steps. The editor of the material loads 128 texture resources in advance. Once the user has chosen one of them through the menu wheel, texture sampling and normal map updates are done in less than 3 frames. The roughness can be changed to 0.1 to 0.9 and the metallicity parameter can be changed to 0.0 to 1.0. Every change causes the local lighting to be recalculated.

The lighting adjustment module allows users to drag the light source position and displays the illuminance contour distribution in real time. Color temperature adjustment uses a slider control, continuously adjustable from 2700K for warm light to 6500K for cool light, and brightness adjustment ranges from 100 to 2000 lux. Table 1 lists the seven types of modifiable design elements supported by the system and their parameter configurations.

TABLE 1. Modifiable Design Element Parameter Configuration Table

Design elements	Correction method	Parameter range	Precision stepping	Rendering response time
Furniture placement	3D drag	±10 meters	0.1 meters	16ms
Furniture rotation	Touchpad rotation	0-360 degrees	5 degrees	16ms
Wall material	Menu selection	128 presets	Discrete switching	48ms
Flooring material	Menu selection	128 presets	Discrete switching	48ms
Light source position	Ray drag	±15 meters	0.2 meters	33ms
Light source color temperature	Slide bar adjustment	2700-6500K	100K	33ms
Light source brightness	Slide bar adjustment	100-2000 lux	50 lux	33ms

Table 1 shows the modified parameter constraints and rendering performance indicators set by the system for different design elements. Furniture elements are operated using a continuous drag-and-drop method to ensure that the single-frame rendering time is controlled within 11.1ms to maintain a stable 90fps, matching the native refresh rate of the HTC Vive Pro 2 and minimizing latency-induced motion sickness. Material elements achieve fast switching through pre-loading of the texture pool, extending the response time to 48ms while still maintaining a good interactive experience.

IV. RESULTS AND DISCUSSION

A. ANALYSIS OF THE EFFECTIVENESS OF DESIGN DEFECT IDENTIFICATION

In the experiment, 36 environmental design professionals were recruited randomly in an experimental group and a control group of 18 participants each. The experimental group was tested with the help of VR immersive evaluation system that was outlined in this paper whereas the control group was tested with traditional 2-D drawings and 3-D static renderings. The test objects were three office space design schemes, which had 12 fixed design faults, such as, the use of the inappropriate furniture sizes, irrational lighting planning, discontinuous circulation patterns, and blocked vistas. All the evaluations were set to 45 minutes. The type, number, and the location of the flaws that were detected by the participants were noted. This study was approved by the Ethics Committee of Nantong Institute of Technology, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form. The accuracy of the identification results was checked by three senior designers.

Table 2 shows that the experimental group identified an average of 10.3 defects across the three schemes, while the control group identified an average of 6.8 defects. The experimental group achieved an accuracy rate of 88.8 % in defect identification, compared to only 61.8 % in the control group, representing an improvement of 43.7%. This difference is mainly attributed to the 1:1 realistic scale perception provided by the VR environment; the virtual walking experience directly exposes spatial flow problems that are difficult to reflect on a floor plan. The accuracy data indicates that the VR system effectively reduces the false positive rate.

TABLE 2. Comparison of Design Flaw Identification Results Between the Two Groups

Scheme number	Preset total number of defects	Experimental group identifications	Control group identifications	Experimental group accuracy	Control group accuracy
Option A	12	10.3	6.8	88.3%	61.2%
Option B	12	10.7	7.2	91.5%	65.4%
Option C	12	9.8	6.5	85.7%	58.9%

B. COMPARISON OF SOLUTION ITERATION EFFICIENCY AND USER SATISFACTION

The experiment was chosen to work with 24 residential interior design projects, and 12 design firms were to optimize their designs in both traditional and VR system as presented in this paper. The conventional process involved a linear workflow including manual floor plan amendments, an average 48-hour rendering queue for high-resolution static images, physical travel for face-to-face client meetings, and a protracted secondary revision cycle requiring total scene re-renders. The VR system enabled a direct indication of problems by clients and viewing of changes in action in a virtual setting, eliminating the need for off-site rendering and travel. The VR system enabled a direct indication of problems by clients and viewing of changes in action in a virtual setting. The length of time spent on a particular project in terms of time taken to first submit a draft up to the final confirmation of the project to the client was counted as iteration cycle indicator. The client satisfaction was rated on a Likert scale with the maximum score of 10 points evaluating five dimensions including spatial perception accuracy, the design understanding, decision-making confidence, the efficiency of communication, and the total satisfaction. There were 48 clients who responded to the questionnaire of the overall score calculated.

TABLE 3. Comparison of Solution Iteration Efficiency and User Satisfaction

Project type	Experimental group iteration cycle (days)	Control group iteration cycle (days)	Experimental group satisfaction score (points)	Control group satisfaction (scores)
Small apartment	7.2	19.5	8.7	6.5
Medium-sized residential units	8.6	22.8	9.0	6.9
Large residential units	9.1	24.7	9.1	7.0
Duplex	8.8	23.2	8.8	6.8
Office space	7.9	20.1	8.9	6.7
Average value	8.3	22.1	8.9	6.8

63.7 % shorter than that of the control group (22.1 days), and this trend was consistent across different project types. The iteration cycle for large apartments (9.1 days) was 1.9 days longer than that for small apartments (7.2 days), reflecting the impact of spatial complexity on efficiency

and indicating that the VR system has stable efficiency improvements for projects of different sizes. User satisfaction in the experimental group averaged 8.9 points, a 30.9% increase from the control group's 6.8 points. Medium-sized apartments had the highest satisfaction score of 9.0 points, while duplex apartments had a slightly lower score of 8.8 points, which is related to the need for frequent perspective switching in VR due to the vertical relationship between duplex spaces. Office space satisfaction (8.9 points) was similar to that of residential spaces, verifying the system's applicability to different functional spaces.

C. DISCUSSION OF APPLICATION LIMITATIONS

The hardware poses a usage challenge to older users; some of the customers who are above 60 years old developed spatial orientation challenges upon wearing headset and needed staff assistance to assess it, which consumes more time. Symptoms of motion sickness, including nausea was also a side effect of long immersion in 8 percent of the participants predominantly when they were subjected to fast changes of scenes or big head movements and the maximum time to be spent on a single evaluation was 30 minutes. This was primarily observed during complex furniture manipulation tasks where rendering latency occasionally fluctuated near the 11.1ms threshold, suggesting that maintaining a consistent 90fps is critical for user comfort during interactive correction phases. Although the preset materials in the material library reproduce common types, the reproduction of custom material, like special stone textures and custom crafted art paints, is not as accurate enough that it has to be complemented by physical samples to make the decision. The simulating capabilities of the system in changing the atmosphere of outdoor scenery and natural light are poor, as it could not reflect the realistic light effects of various seasons and times of the days and influence the quality of assessments of window design and shading systems.

V. CONCLUSION

This paper builds on the immersive assessment and interactive remediation of environmental design systems by utilizing virtual reality to simulate the complex spatial morphology and anisotropic mechanical properties of industrial components. This approach enables a more precise evaluation of how material distribution and functional material density influence the overall structural integrity and user experience within the virtual environment. The four-layer architecture allows to reconstruct the scenes with high fidelity, as well as allows to interactive edit the design schemes in real-time. The system incorporates eye tracking, path recording and behavioral analysis technologies to formulate a multi-dimensional index system of quantitative evaluation, including spatial layout rationality, visual comfort, and functional accessibility, to overcome the drawbacks of the tradition two dimensional drawings and static depictions. By roaming around the virtual space, gaze routes, movement-paths and dwell-behaviors are automatically gathered by the system,

and they create objective measures of evaluation. The interactive correction module allows real-time change of the furniture layout, type of material used, and the parameters of lighting, and the change result is immediately rendered, without the need of expensive repetitive communication between the design iteration process and the user.

Experiments confirm that the system excels in identifying design defects related to material morphology and spatial distribution, providing a scientific decision-making tool that enhances scheme optimization efficiency and user satisfaction. By integrating the anisotropic mechanical properties of industrial textiles into the virtual assessment, this approach establishes a novel evaluation procedure for the area of environmental design.

AUTHOR CONTRIBUTIONS

Fei Hu designed, collected and analyzed the data, and drafted the manuscript. Fei Hu conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Fei Hu participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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HUMAN RESEARCH SUBJECTS

This study was approved by the Ethics Committee of Nantong Institute of Technology, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

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REFERENCES

- [7] N. N. Correia, S. Jürgens, R. Masu, et al., "Performative Virtual Scenes: A Dynamic VR Environment Design Approach," Springer, Cham, 2021, doi: 10.1007/978-3-030-89394-1_8.
- [8] T. Tsunajima and N. Nishiuchi, "Visual Environment Design of VR Space for Sequential Reading in Web Browsing," 2020, doi: 10.1007/978-3-030-50729-9_18.
- [9] N. Shan, "Research on Indoor Environment Design Based on VR Technology and Wireless Sensor Network," Microprocessors and Microsystems, 2021, 103999, doi: 10.1016/j.micpro.2021.103999.
- [10] J. Luo, V. Aumeboonsuke, and Z. He, "Artificial Intelligence and Digital Museum VR Environment Design Based on Embedded Image Processing," Applied Mathematics and Nonlinear Sciences, vol. 9, no. 1, 2024, doi: 10.2478/amns-2024-0116.

- [1] P. Huang, L. Wang, Z. Xiao, et al., "Research on natural interaction method of virtual hand in VR environment," Mechanical Design and Manufacturing, no. 7, pp. 4, 2021, doi: 10.3969/j.issn.1001-3997.2021.07.063.
- [2] X. Wang and C. Meng, "Research on optimization of indoor environment design scheme based on VR technology," Education and Teaching Forum, no. 17, pp. 2, 2020, doi: CNKI:SUN:JYJU.0.2020-17-061.
- [3] M. Wang, "Analysis of the application of VR virtual reality technology in interior design effect display," Architectural Technology Research, vol. 3, no. 11, pp. 27-28, 2021, doi: 10.12238/btr.v3i11.3498.
- [4] S. Jiang, R. Jia, L. Dan, et al., "A brief analysis of the practical teaching of virtual intelligent manufacturing by applying VR technology in industrial design engineering," Innovation and Practice of Teaching Methods, vol. 3, no. 10, pp. 191, 2020, doi: 10.26549/jxjffxysj.v3i10.5414.
- [5] J. Yuan, "Research on environmental design teaching based on VR technology," Art Education Research, no. 19, pp. 154-156, 2023, doi: 10.3969/j.issn.1674-9286.2023.19.055.
- [6] A. Karagzler and D. D. Karagzler, "VR and AR in Teaching 3D Environment Design for Video Games," Springer, Cham, 2021, doi: 10.1007/978-3-030-65060-5_19.