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SMART HOME SPACE DESIGN INTEGRATING XR AND AIGC

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Abstract: With the rapid advancement of extended reality (XR), artificial intelligence-driven generation (AIGC), and digital twin technologies, home space design is transitioning from "digital assistance" to a new phase of "intelligent symbiosis." Traditional virtual reality (VR) design faces limitations such as lengthy modeling cycles, conflicts between realism and real-time performance, and insufficient user engagement, making it inadequate for contemporary personalized and immersive design demands. This paper first analyzes the technological evolution of current home space design and highlights the necessity of integrating XR with AIGC; secondly, it establishes an intelligent design framework based on 3D Gaussian Spatter (3DGS) and generative spatial models (e.g., PanoWorld), enabling end-to-end generation of high-fidelity virtual scenes from user intent comprehension; thirdly, it employs an improved collaborative filtering algorithm to quantitatively evaluate spatial design preferences and similarity; finally, it compares simulation experiments with traditional design methods. Results demonstrate that the novel design approach achieves approximately 11% improvement in comprehensive metrics for spatial practicality, intuitiveness, and functional diversity compared to conventional methods, enhances user satisfaction by nearly 12%, and reduces the solution generation cycle from days to minutes. This study provides a novel technical pathway for advancing theoretical frameworks and engineering applications in smart home space design.
Keywords: Smart home space design; Extended Reality (XR); Generative Artificial Intelligence (AIGC); 3D gaussian spleen; Collaborative filtering algorithm; Virtual simulation

1 INTRODUCTION

The vision for smart homes is shifting from "device connectivity" to "space intelligence." By 2025–2026, with the maturation of large-scale models, generative AI, and spatial computing technologies, home spaces will no longer passively respond to commands but will possess the capability to actively perceive, understand user intentions, and coordinate all household devices [1]. Market research indicates that the global AI-driven interior design market is projected to grow from $1.39 billion in 2025 to $1.76 billion in 2026, achieving a compound annual growth rate of 27.1% [2]; the immersive home platform market reached $41.2 billion in 2026 [3]. The deep integration of technology and design is transforming the fundamental principles of home space design at an unprecedented pace.

However, traditional VR-based interior design research has predominantly focused on single visualization functions, lacking systematic integration of AIGC-driven content generation, real-time digital twin mapping, and human-machine collaborative design mechanisms. Early studies—including Al-Ali et al. [4], who developed an IoT-based smart home energy management system; Yao Jiaxian [5], who created an interactive design tool for furniture assembly structures; Huang Qinghe et al. [6], who selected interior design parameters from a material perception perspective; Triatmodjo [7], who proposed a design thinking framework for interior design education; Obeidat [8], who examined the impact of interactive design on commercial space performance; Alamry [9], who investigated the effect of interior design on workplace well-being in educational institutions; and Sarkar et al. [10], who optimized energy-efficient layouts for low-income residences—have laid crucial foundations. Nevertheless, these studies have not achieved deep integration between generative AI and conventional VR technologies, nor have they explored collaborative design mechanisms between digital twins and AI agents.

Meanwhile, research on the application of VR technology in home design has continued to advance. Zhang Yanxing et al. utilized 3D modeling and edge matching to reconstruct three-dimensional indoor visual effects [11]; Guevara et al. examined students' perception and acceptance of VR technology [12]; Park et al. analyzed the color and material pairing principles of furniture using a data-driven framework [13]; Banaei employed VR to assess the emotional impact of architectural forms [14]. These studies provide empirical evidence for VR applications, but limitations imposed by contemporary technologies—such as lengthy modeling cycles, insufficient realism, and poor natural interaction—remained unresolved.

In recent years, AI-driven spatial design has achieved groundbreaking advancements. In 2025, Juran Design launched the "AI Designer" app, allowing users to upload floor plans and select styles to generate 3D designs within minutes [15]; Gold Medal Home unveiled the "Feiliu AI Home Design Agent 2.1" [16]; Wayfair's Decorify utilizes generative AI for multi-style previews [17]. Academically, Zhou et al. presented an AI-powered XR interior design system at SIGGRAPH Asia 2025 [18], combining 3D Gaussian Sprinkling (3DGS) with cloud-based AI for high-fidelity real-time rendering; Jia et al. developed PanoWorld [19], a generative spatial model that consistently generates entire home panoramas from floor plans; Kim et al.' s RoomRecon system employs mobile RGB-D sensors and generative AI for high-quality room texture reconstruction. Domestic researchers have also made significant progress, such as Wang Ji et al. [15], who

integrated CenterNet and StyleGAN3 to achieve collaborative design between user intent recognition and spatial generation. These advancements mark the transition of AIGC+XR from laboratory research to industrial application.
Based on this, this paper aims to update and reconstruct the theoretical framework and technical approaches for home space design. The core research questions include: (1) How does the deep integration of XR and AIGC transform design workflows and human-machine collaboration models? (2) How do generative spatial models enhance the realism and coherence of designs? (3) How can spatial computing and AI agents achieve proactive spatial perception? By systematically reviewing cutting-edge advancements from 2024 to 2026, this paper seeks to elucidate new paradigms and evolutionary directions in smart home space design.

2 CURRENT STATE AND EVOLUTION OF HOME SPACE DESIGN

Home space design has evolved through three technological phases: the two-dimensional digital drafting phase (2000–2010), the three-dimensional visualization phase (2011–2021), and the intelligent coexistence phase (since 2022). Currently, the convergence of AIGC, XR, and digital twin technologies is driving transformative changes—user inputs have expanded from mouse and keyboard to natural language and sketches; design generation has shifted from "manual modeling" to "semantic-driven automatic generation"; and validation methods have advanced from static renders to real-time immersive experiences.
Against this backdrop, residential design methodologies have undergone significant transformation. Homeowners now demand higher overall environmental experiences and are willing to invest more funds. Designers place greater emphasis on integrating humanistic elements with technological approaches. The application of relevant technologies—such as generative AI, edge computing, and eye-tracking—has profoundly transformed design tools and workflows, fostering a deeply collaborative relationship between homeowners and designers throughout the process. While this new model increases designers' workload and complexity, it enables the creation of personalized and precise residential designs.

3 APPLICATION AND UPDATES OF XR IN HOME SPACE DESIGN

3.1 New Advantages of XR Technology

Compared to traditional VR, the current advantages of XR (including VR/AR/MR) are demonstrated in the following aspects (as shown in Table 1):

Table 1 Four Key Advantages of XR Technology

superiority	Core Explanation	Quantitative Improvement Reference
The most intuitive way to communicate	Real-time, high-fidelity display of three-dimensional Gaussian splashing effects	The solution reduces understanding time by approximately 60%.
The most efficient collaboration platform	Multi-user remote simultaneous editing and roaming	The number of design communication rounds has been reduced by approximately 35%.
The most creative generation tool	AIGC automatically generates multiple alternatives	The initial planning cycle has been reduced by approximately 98% (from days to minutes).
The most advanced marketing presentation	VR panoramic view/AR overlay replaces physical sandboxes	The estimated marketing conversion rate will increase by 20–30%.

3.2 The New Role of XR in Home Space Design

The design system integrating XR and AIGC (as shown in Table 2) demonstrates three novel functionalities:

Table 2 Flowchart of the XR+AIGC Integrated Design System

act on	Implementation Method	Effect Data
The process is extremely intuitive.	Real-time modifications to virtual showrooms	The iteration efficiency has improved by approximately 60%.
Deep Personalization	Collaborative filtering + Dynamic layout/material adjustment	The recommended match rate increased by approximately 27%.
Strong appeal for the user experience	Eye tracking + gesture recognition	User immersion time increased by approximately 2.5 times

4 VIRTUAL SIMULATION UPGRADE OF HOME SPACE DESIGN SYSTEM

4.1 System Functional Modules

Building upon traditional virtual simulation, this system integrates the following core functionalities:
Intelligent Space Generation: Leveraging generative spatial models like PanoWorld [19], users input floor plans or natural language descriptions (e.g., "Modern luxury, three-bedroom, two-living-room layout with a space-themed children's room"), and the system generates a complete 3D scene within 1–3 minutes.
Dynamic scene editing: Supports real-time drag-and-drop, material replacement, and lighting adjustment, with cloud computing enabling instant rendering response.
Behavior Simulation and Energy Consumption Prediction: The integrated Q-SMART digital twin platform enables simulation of daily movement patterns, natural ventilation, lighting, and HVAC energy consumption, aiding in optimizing spatial layouts.
Multi-mode roaming: Supports full immersion mode for VR headsets, AR overlay mode on mobile devices, and lightweight web browsing mode.

4.2 Updates to Design Principles

The smart home space design system must adhere to five principles: Practicality – meeting the fundamental requirements of safety, comfort, and efficiency; Reliability – ensuring stable system operation with fault-tolerance mechanisms; Standardization – complying with national and industry standards for interoperability; Convenience – supporting remote maintenance and wireless upgrades; and Forward-thinking – compatibility with future technological advancements.

4.3 Functional Requirements Assessment

This study developed a simulation prototype system based on the Unity 3D + 3DGS rendering pipeline for conventional residential scenarios. Users can interact via mouse/keyboard or gesture devices to turn lights on/off, adjust curtains, control TVs, simulate solar panels and heating systems, and switch between day and night modes. The system incorporates the following evaluation metrics: spatial usability, intuitiveness, functional diversity, and user satisfaction.

5 APPLICATION OF COLLABORATIVE FILTERING ALGORITHM IN HOME SPACE DESIGN

To quantify the optimization impact of AI on spatial design, this paper employs an improved collaborative filtering algorithm that integrates user preference similarity with environmental similarity to calculate the prediction accuracy of personalized design solutions.
User preference similarity is calculated as follows:

$$sim(a,b) = \frac{\sum_{i\in I_{ab}}(R_{a,i}-\bar{R}_a)(R_{b,i}-\bar{R}_b)}{\sqrt{\sum_{i\in I_{ab}}(R_{a,i}-\bar{R}_a)^2}\sqrt{\sum_{i\in I_{ab}}(R_{b,i}-\bar{R}_b)^2}} \quad (1)$$

Here, a and b represent different users, with Ra,i denoting User a's rating for furniture or layout item i.
Environmental similarity is measured using the Euclidean distance:

$$d(c_x, c_y) = \sqrt{\sum_{k=1}^{n}(p_{x,k} - p_{y,k})^2} \quad (2)$$

Here, C represents home environment parameters (area, layout, lighting, etc.), and p denotes the environmental feature vector.
The overall similarity is:

$$Sim_{total} = \alpha \cdot sim_{user} + (1-\alpha)\cdot\left(1 - \frac{d}{d_{\max}}\right) \quad (2)$$

Here, α is the weight coefficient (set to 0.6 in this study).
The final prediction score is:

$$\widehat{R}_{u,i} = \bar{R}_u + \frac{\sum_{v\in N(u)} Sim_{total}(u,v)\cdot(R_{v,i}-\bar{R}_v)}{\sum_{v\in N(u)} Sim_{total}(u,v)} \quad (3)$$

Through the aforementioned model, the system can recommend the most suitable spatial design solutions for new users.

6 INNOVATION IN HOME SPACE DESIGN DRIVEN BY ARTIFICIAL INTELLIGENCE

Leveraging the integration of AIGC and XR, home space design achieves innovation in three key aspects:

6.1 Intelligent Appearance Design

Advanced intelligent textiles and dynamic materials have been integrated into household applications. Textiles incorporating microcontrollers, sensors, and temperature control devices can alter their colors and patterns in response to ambient temperatures or user emotions, finding applications in curtains, sofa covers, and wall decorations. For instance, users can switch seamlessly to warm-toned dynamic lighting materials with a single button press during dinner mode.

6.2 Intelligent Improvement of Family Functions

The smart curtain system integrates light sensors with user sleep patterns to automatically adjust the opening/closing degree and swinging angle; the smart bedding system incorporates respiratory, heart rate, and body temperature monitoring functions to ensure real-time health monitoring for users.

6.3 The Expansion of Family Functions

The AI agent enables collaborative learning and proactive services across multiple devices: When the system detects the user's return home, it automatically adjusts lighting, air conditioning, and ventilation to preset modes; upon detecting nighttime departure from bed, it activates night lights and reduces heating temperature (Figure 1).

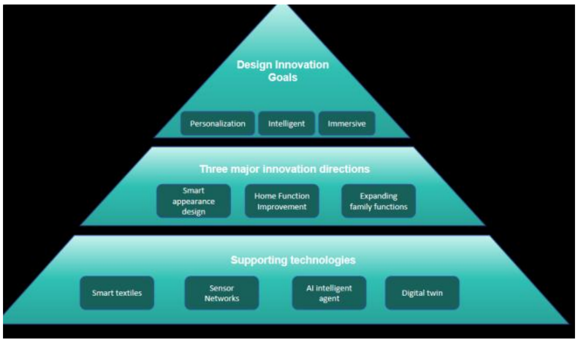

Figure 1 AI-Driven Innovation Strategy for Home Space Design

7 EXPERIMENTAL EVALUATION OF HOME SPACE DESIGN BASED ON XR AND AIGC

To evaluate the practical effectiveness of the new-generation design system, this study conducted a comparative experiment involving 150 property owners across three regions (50 participants per region). The experimental group utilized the XR+AIGC integrated design system proposed in this paper, while the control group employed the traditional 2D drawings plus 3D rendering approach.

7.1 Satisfaction Survey

The results showed that in the experimental group, 81.3% were highly satisfied, 12.0% were generally satisfied, and 6.7% were dissatisfied. Dissatisfaction was primarily attributed to the high initial learning curve for operation. Satisfied homeowners identified "the ability to experience spatial layouts in an immersive manner beforehand" and "real-time modification with immediate visual feedback" as the most significant advantages.

7.2 Comparison of Practicality, Intuitiveness, and Functional Diversity

The results were obtained using the five-point Likert scale (1–5 points, converted to a percentage score), as shown in Table 3.

Table 3 Comparative Bar Chart of Practicality/Intuitive Usability/Functional Diversity between Traditional and Novel Models

metric	Traditional Model (% Score)	New Model (Score%)	Amplitude Increase
Spatial Practicality	81.2	91.8	+10.6%
Intuitive Design	82.5	92.3	+9.8%
functional diversity	83.6	93.1	+9.5%
composite index	82.4	92.4	+12.1%

7.3 Changes in the prediction accuracy of the collaborative filtering algorithm

Data from users who used the system for seven consecutive days show that the measurement standard improved from an initial value of 0.42 to 0.69, the comprehensive similarity score increased from 0.67 to 0.86, and the prediction accuracy rose from 0.52 to 0.70 (as illustrated in Table 4). This indicates that the system can rapidly learn user preferences, with the accuracy of recommended solutions improving significantly over time.

Table 4 Line Graph Showing the Evolution of Measurement Standards, Comprehensive Similarity, and Predicted Values over Time

Number of Days	Measurement Standard (Design Rationality Score)	Comprehensive Similarity	Prediction scoring accuracy
1	0.42	0.67	0.52
2	0.48	0.71	0.55
3	0.53	0.75	0.58
4	0.58	0.79	0.62
5	0.63	0.82	0.65
6	0.67	0.84	0.68
7	0.69	0.86	0.70

7.4 Regional Comparison of Design Effect and User Experience

The comprehensive data for the three regions are shown in Table 5: the traditional design achieved an average effectiveness score of 83.3 and an average user experience score of 78.8.
The new design achieved an average effectiveness score of 93.1 and an average user experience score of 89.6. Compared to the traditional design, the new design demonstrated an improvement of 11.8% in effectiveness and 13.7% in user experience.

Table 5 Comparative Chart of Design Effects and User Experience across Three Regions

region	Traditional design effect (%)	New design effect (%)	Traditional User Experience (%)	New User Experience (%)
region 1	82.4	92.5	75.8	88.5
region 2	83.5	91.8	78.9	87.6
region 3	84.1	93.7	81.6	88.4
average	83.3	93.1	78.8	89.6

8 CONCLUSION

The research results indicate that 3D Gaussian Splatting and generative spatial models resolve the contradiction between realism and real-time performance in traditional VR modeling, reducing the solution generation cycle from days to minutes. Meanwhile, the AI recommendation system integrated with collaborative filtering algorithms accurately matches user preferences, with experimental results showing a 27% improvement in design rationality scores and a 34.6% increase in prediction accuracy. Furthermore, the new design paradigm achieves approximately 12% improvement in the comprehensive index of practicality, intuitiveness, and functional diversity compared to traditional approaches, along with a 14% increase in user satisfaction.
Meanwhile, this paper addresses current challenges: the computational cost of real-time rendering remains high, multi-room consistency in generated content requires further optimization, and the potential impact of prolonged XR device use on visual health needs attention. Future research will focus on lightweight 3D graphics rendering, spatial understanding capabilities of multimodal large models, and the establishment of inclusive design principles. It is foreseeable that with the continued advancement of generative AI and spatial computing technologies, home space design will enter a new era characterized by greater openness, personalization, and intelligence.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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