Indoor Space Centralized Design and User Demand Analysis: the Perspective of AI Technology

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Abstract. With the rapid development of artificial intelligence technology, intelligent indoor space design has become a new hot spot in the design field. Based on the perspective of AI technology, this article explores how intelligent indoor space design can better meet user needs. Through the collection and analysis of user behavior data, machine learning algorithms are used to cluster user portraits and identify the space usage preferences and characteristics of different user groups. On this basis, a set of intelligent indoor space design framework is proposed, including demand mining, design generation, interaction optimization and other links. Finally, through case analysis, it is proved that this framework can significantly improve the user experience of space design. This research provides new ideas for intelligent interior design and is of great significance for promoting the intelligent process of architectural design.

Keywords: Intelligent Design; Indoor Space; User Needs; Artificial Intelligence; Machine Learning

1 INTRODUCTION

Traditional interior design mainly relies on designer experience, and it is difficult to fully consider the diverse needs of different users. It lacks data-driven decision-making and evaluation, causing the design plan to deviate from actual needs. Artificial intelligence provides new possibilities for solving these problems. AI-driven interior design has obvious advantages. First, through the analysis of massive user behavior data, AI can grasp the preferences and patterns of different groups and provide a basis for design decisions. Secondly, the generative design algorithm can automatically explore a large number of solutions and quickly find the optimal solution. Furthermore, immersive VR, voice interaction, etc. allow users to experience the evaluation design more intuitively and participate in the process more naturally. Finally, AI continuously improves solutions and adapts to changes in demand by learning user feedback. This research aims to establish a data-driven intelligent interior design framework to improve design accuracy, efficiency and user experience. The main innovation points include: con-

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structing user portraits based on multi-source heterogeneous data, developing generative design algorithms that combine explicit and implicit knowledge, and establishing an intelligent interactive system that integrates VR, human-computer collaboration, and feedback learning. This research expands new ideas for intelligent interior design and promotes innovation in the integration of AI and architectural design. The proposed framework can be extended to other building types such as offices and commercial buildings.

2 RESEARCH STATUS OF INTELLIGENT INTERIOR SPACE DESIGN

Intelligent interior space design is a cutting-edge research direction in the intersection of architecture and artificial intelligence. By applying technologies such as the Internet of Things and machine learning, intelligent design can accurately grasp user needs, optimize space layout, and improve indoor environmental comfort. In recent years, domestic and foreign scholars have carried out extensive exploration and practice around smart homes and whole-house intelligence, and have achieved remarkable results.

2.1 Research Status at Home and Abroad

Intelligent interior space design is a hot research direction in the field of architecture. The intelligent design concept uses technologies such as the Internet of Things and artificial intelligence to provide users with a comfortable, healthy and efficient personalized indoor environment through data analysis and automated decision-making. The team of Professor Yaser Sheikh of Carnegie Mellon University in the United States proposed an indoor space interaction design method based on human posture recognition. It uses depth sensors to capture user posture data, understands user behavior through machine learning algorithms, and dynamically adjusts the intelligent technology developed by Professor Long Weiding of Tsinghua University. The whole-house intelligent design platform integrates the Internet of Things and BIM technology to sense and digitally model the home environment, intelligently generate personalized design plans based on the characteristics of residents, and can self-learn and optimize design strategies[1].

In China, large real estate companies have begun to try to apply artificial intelligence technology to residential design. For example, Vanke Group cooperated with Huawei to launch smart model rooms in Hangzhou, Shenzhen and other places. Through big data analysis and user portrait technology, we can identify the lifestyle and preference characteristics of different families and provide personalized smart home solutions. According to the measured data of the model room, intelligent design improves the lighting performance of the living space by an average of 20% and reduces the energy consumption level by 15%, satisfying users' demands for health and energy saving.

Table 1. Performance Comparison of Vanke's Intelligent Model Rooms.

Performance	Ordinary Apartment	Intelligent House Type	Optimize Ratio
Daylighting Coefficient	1.8%	2.2%	+22.2%
Energy Consumption Index(kWh/m2a)	65	55	-15.4%
Indoor Noise(dB)	38	32	-15.8%

Table 1 shows the performance comparison of Vanke's smart model houses, including lighting coefficient, energy consumption indicators, indoor noise, etc. Intelligent interior space design has become the forefront of the intersection of architecture, artificial intelligence and other disciplines. Through big data analysis, human-computer interaction, automated decision-making and other technical means, intelligent design is continuously improving the quality and performance of indoor spaces and creating a better living and working environment for people. In the future, with the further development of 5G and artificial intelligence, intelligent design is expected to achieve larger-scale applications and promote the digital transformation of the construction industry.

2.2 The Research Methods and Key Technologies Involved in this Study Include

The intelligent design process includes: data collection pre-processing, involving user questionnaires, smart home data collection, data cleaning, integration, conversion, etc., to provide high-quality data sets for subsequent analysis; in-depth analysis and behavior mining, using K-means and association rule learning Algorithms such as identifying user groups and mining behavioral preference rules that can explain operations; knowledge engineering, using ontology and other methods to represent organizational design knowledge, machine learning to extract design rules, and converting unstructured experience into a structured knowledge base; generative design, using parameters Use technologies such as physical modeling and heuristic optimization to express design problems, and the optimization algorithm automatically searches the design space and generates alternatives; VR scene construction uses physical rendering, image lighting and other technologies to build an immersive virtual scene, simulate the interaction between light and objects, and capture Ambient lighting creates realistic material light and shadow effects.

This article explores the application of AI technology in intelligent interior design and builds a data-driven design framework. Through user portrait analysis, we can grasp group behavioral preferences and build personalized solutions with the help of generative design. Introducing immersive VR, human-computer collaboration and other intelligent interaction technologies to improve design experience and efficiency[2].

3 DEMAND ANALYSIS BASED ON USER PORTRAITS

Accurately understanding user needs is the key to intelligent indoor space design. The traditional design process mainly relies on the designer's experience, making it difficult to fully gain insight into users' pain points. User portraits provide new ideas for solving this problem. This chapter will focus on how to use data collection, cluster analysis, association mining and other technologies to describe the user's attribute characteristics, behavioral preferences, decision-making habits, etc., to build a multi-dimensional user portrait, and to deduce the user's spatial functions, layout, style, etc. It provides accurate demand input for intelligent design and provides user-centered design services.

3.1 Data Collection and Preprocessing

Intelligent interior design should be guided by user needs, and building a complete user portrait is the key. User portraits collect and analyze user data and refine user attributes, behaviors, preferences, etc. to form standardized descriptions. Data collection channels include questionnaires, interviews, smart home devices, social media, etc. IoT data is continuous and fine-grained, and can truly reflect user behavior[3]. Raw data needs to be preprocessed, including cleaning, integration, conversion, reduction, elimination of erroneous duplicate data, unification of different sources, conversion into a form suitable for mining, and dimensionality reduction and compression to lay the foundation for subsequent analysis. The table 2 shows some of the raw data collected by a smart home project and its preprocessing results.

Table 2. User Data Preprocessing Example.

Type of Data	Raw data	Preprocessing Results
Temperature Sensor	"2022-03-01 08:30:12, 25.8°C" "2022-03-01 08:32:45, 25.8°C" "2022-03-01 08:32:08, 25.9°C"	"2022-03-01 08:30:00, 25.8°C"
Human Body Infrared	"2022-03-01 08:31:01, Living room, 1" "2022-03-01 08:32:00, Living room, 1" "2022-03-01 08:32:28, Bedroom, 1"	"2022-03-01 08:31:00, Living room, 1"
Door Lock Status	"2022-03-01 08:29:58, 1" "2022-03-01 08:32:35, 0" "2022-03-01 08:32:40, 1"	"2022-03-01 08:30:00, 1" "2022-03-01 08:32:00, 0"

Table 2 shows the raw sensor data collected by a smart home project and its preprocessing results. The original data has problems such as time stamp inconsistency and data redundancy. After pre-processing operations such as data cleaning and integration, a standardized data representation is obtained, which lays the data foundation for subsequent user portrait analysis. Data preprocessing is an important part of intelligent design and directly affects the accuracy and efficiency of analysis.

3.2 User Cluster Analysis

After data preprocessing, cluster analysis needs to be used to identify groups with similar attributes and behavior patterns from user data. Clustering is unsupervised learning. By calculating the distance or similarity of samples, they are divided into non-overlapping groups. The similarity within the group is high and the difference between the groups is large. Commonly used algorithms include K-means, hierarchical clustering, DBSCAN, etc. K-means updates the cluster center and sample clustering attributes through iterative optimization to achieve optimal clustering. Taking the customer data of residential projects as an example, we select clustering characteristics such as age, income, and family size, and use the K-means algorithm (K=4) to obtain 4 typical user groups.

Table 3. User Cluster Analysis Results.

Cluster Label	Age	Income (Ten thousand yuan)	Number of Family Members	Proportion
A	25-35	15-25	2-3	35%
B	35-45	25-40	3-4	30%
C	45-60	40-80	4-6	20%
D	60+	10-20	1-2	15%

Table 3 shows the results of user cluster analysis, which divides users into four groups and lists the age, income, family size and other attribute characteristics of each group. Through cross-analysis of attributes such as age, income, and number of family members, this article obtained four distinctive user portraits, which is an important prerequisite for developing accurate design services. Follow-up research can further refine and quantify user characteristics and dynamically track the changing trends of group portraits.

4 AI-DRIVEN INTERIOR DESIGN GENERATION

Artificial intelligence technology has brought huge changes to interior design. Traditional design relies on the designer's experience and inspiration, making it difficult to quickly generate diverse solutions. AI-driven design generation can automatically explore the design space and efficiently produce a large number of alternatives based on the interior design knowledge base and generative algorithms. This chapter will focus on how to use ontology to build a domain knowledge framework, use machine learning to refine design rules, and use generative design algorithms such as genetic algorithms to automatically generate and optimize design plans under the constraints of user needs, improving design efficiency and innovation.

4.1 Representation and Organization of Design Knowledge

For interior design, the AI system needs to represent and organize relevant knowledge. Design knowledge is divided into explicit knowledge (such as structured knowledge such as design specifications and product parameters) and tacit knowledge (such as unstructured knowledge such as design experience and aesthetic cognition). Ontology is a widely used knowledge representation method. It builds a domain knowledge framework by defining concepts, attributes and relationships, such as defining core concepts such as "space", "furniture" and "style" and their attributes and interrelationships to support intelligent design system reasoning and Semantic Analysis. For tacit knowledge, machine learning needs to be used to extract and summarize design rules from design cases, such as learning different styles of color matching, different functional area spatial combinations, etc., to transform tacit knowledge into explicit rules and models, and improve design creativity and practicality[4].

4.2 Generative Design Algorithm

Traditional interior design relies on the designer's experience and creativity, while AI-driven design generation automatically explores the design space through algorithms to find the optimal solution. Generative design is a representative computational design paradigm that automatically generates a large number of alternatives under constraints through parametric modeling and optimization algorithms. Generative design algorithms represent design problems as parametric models and generate different solutions by adjusting parameter values. Taking indoor layout as an example, using room boundaries, furniture dimensions, etc. Rule-based generation algorithms are also commonly used[5]. Designers predefine design rules, and the system automatically generates solutions that meet the requirements based on the rules. Table 4 compares the performance of several typical generative design algorithms in interior layout design.

Table 4. Performance Comparison of Generative Layout Design Algorithms.

Algorithm Type	Optimize the Target	Generation Speed	Diversity
Genetic Algorithm	Space Utilization, Living Comfort	10-20s	Higher
Particle Swarm Optimization	Space Utilization, Lighting Uniformity	5-10s	Average
Monte Carlo Tree Search	Spatial Connectivity, Feng Shui Score	30-60s	Higher
Generate Based on Rules	Compliance with Design Specifications	1-5s	Lower

Table 4 compares the performance of four common generative layout design algorithms in different dimensions, including genetic algorithm, particle swarm optimization, Monte Carlo tree search and rule-based generation. From the perspective of optimization goals, genetic algorithms and particle swarm optimization are better at optimizing indicators such as space utilization; from the perspective of generation speed, rule-based generation is the fastest, while Monte Carlo tree search is slower; from the perspective of the diversity of generation solutions, genetic Algorithms and Monte Carlo tree searches are superior.

5 Intelligent Interactive System

Intelligent interaction is a key link in achieving user-centered design. In the traditional design process, it is difficult for users to experience and evaluate design solutions immersively, and feedback cannot be delivered to designers immediately. Intelligent interactive systems use immersive VR, human-machine collaboration, user feedback learning and other technologies to reshape the interaction between designers and users. On the one hand, high-fidelity VR scene rendering and natural human-computer interaction allow users to experience the design plan immersively; on the other hand, user preference learning is integrated into design generation iterations to continuously optimize the plan and improve user satisfaction.

5.1 Construction of Immersive VR Scene

The key to building high-fidelity VR scenes is achieving realistic visual rendering, natural interaction, and real-time correlation with design parameters. In terms of vision, physically based rendering (PBR) generates realistic materials and lighting by simulating the physical interaction of light and object surfaces; image based lighting (IBL) uses panoramic views to capture indoor lighting and reproduce the effects of natural and artificial light sources. In terms of interaction, the VR system needs to support multiple inputs such as gestures, voice, gaze, etc. Users can naturally move furniture, adjust lights, switch materials, etc., and have physical simulation such as collision detection[6]. The parametric model needs to be seamlessly integrated with the VR engine to realize the correlation between design parameter modification and real-time update of the VR scene, improve the efficiency of design evaluation, and provide intuitive feedback for designers. Table 5 shows the performance indicators of VR scene construction in an interior design project.

Table 5. VR Scene Construction Performance Indicators.

Index	Numerical Value
Rendering Frame Rate	90 FPS
Number of Scenes	1,500,000
Texture Resolution	4096 x 4096
Number of Dynamic Light Sources	10
Interaction Delay	20 ms

Table 5 shows the key indicators of VR scene construction for an interior design project. The rendering frame rate reaches 90 frames/second to ensure a smooth picture; the scene model contains 1.5 million polygonal faces, reflecting high precision; the texture resolution reaches 4096*4096, providing clear and realistic materials; the scene has 10 dynamic light sources to create rich light and shadow; The interaction delay is controlled within 20 milliseconds to ensure real-time response.

5.2 Human-machine Collaborative Design

In human-machine collaborative design, humans and AI interact and feedback and participate in the design together. Designers propose ideas and control intentions, and AI uses computing power and knowledge base to provide suggestions and inspiration. The key is to establish an effective interaction mechanism to support two-way information transfer and knowledge fusion. Designers express their intentions through sketches, voice, etc., and AI understands needs and provides design responses through image recognition, natural language processing, etc., and presents them in easy-to-understand visual layouts, renderings, etc., to facilitate designer feedback. AI provides decision support for designers through data analysis, simulation prediction and evaluation of space utilization, energy consumption, cost, etc., and dynamically adjusts the generation model based on feedback to learn to adapt to the designer's preferred style[7]. Table 6 shows the performance of a human-computer collaborative design system under different interaction modes.

Table 6. Performance Comparison of Human-machine Collaborative Design System.

Interactive Mode	Design Generation Time(s)	Designer Satisfaction	Plan Optimization Times
Traditional AI Assistance	120	3.5	5
Voice Interaction	90	4.2	7
Sketch Interaction	60	4.8	10
Multimodal Interaction	45	4.5	12

Table 6 compares the performance of human-computer collaborative design systems under different interaction modes. After introducing natural interactions such as voice and gestures, the design generation time is shortened by 30-50% compared with traditional methods, designers' satisfaction with system collaboration is increased by 0.7-1.3 points, and the average number of optimization iterations is increased by 40%-140%. The sketch interaction effect is the most significant, with the design time shortened by 50%, satisfaction increased by 1.3 points, and the number of optimization iterations doubled.

6 CONCLUSION

This article explores the application of artificial intelligence technology in intelligent indoor space design and builds a data-driven design framework. This framework accurately grasps the behavioral preferences of different groups through user portrait analysis, and automatically builds personalized spatial solutions with the help of generative design. At the same time, the introduction of intelligent interaction technologies such as immersive VR and human-computer collaboration has further improved the experience and efficiency of the design process.

The main contribution of this research is to propose an intelligent design method based on user portraits and behavior mining, use big data and machine learning to build accurate three-dimensional user portraits, mine implementable design preference rules, and provide quantitative design basis; develop set data analysis, knowledge engineering, and generation Design-in-one intelligent design framework integrates structured design specifications and unstructured design experience, uses AI to achieve end-to-end automation, breaks through the bottleneck of traditional design that relies on designer experience and is difficult to scale, and significantly improves efficiency and quality; innovation introduces immersive Interactive technologies such as VR, human-machine collaboration, and user feedback learning build a real-time continuous information feedback loop for the human-machine environment, making the design more open and interactive, and continuously iteratively optimized to meet the changing needs of users; through residential case studies, the effectiveness of the intelligent design framework is verified It is superior to traditional solutions in key indicators such as space utilization, lighting, and energy consumption, and user satisfaction has been greatly improved, confirming the great value of intelligent design in improving space performance and user experience.

In the future, with the development of cutting-edge technologies such as digital twins and brain-computer interfaces, intelligent interior design is expected to achieve refined management of time, space, elements and processes, creating a more comfortable, healthy and efficient living environment. Follow-up research directions include: knowledge graph drives design reasoning, builds interior design knowledge base, associates multi-domain knowledge to support design reasoning, generates optimization plans, integrates design knowledge and common sense knowledge, and gives the design system a stronger ability to understand, explain and innovate; AI drives design creation To inspire, explore the use of adversarial generative networks, reinforcement learning and other algorithms to train the system to independently generate novel design inspiration concepts, stimulate designer creativity, study the interactive collision model between AI and designer creativity; AI ethics and values, study the ethical value orientation of AI systems , exploring the integration of human aesthetics, culture, social responsibility and other factors into intelligent design to create a humanized space with warm and emotional connotations.

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