A Multi-Person Collaborative Design Method Driven by Augmented Reality

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***Abstract*—The current interior design of commercial buildings is facing innovative challenges, requiring a balance between aesthetics, functionality, and economic benefits. The design industry faces challenges in interdisciplinary integration, lack of standardized processes, and limitations of traditional design methods in complex situations. Although virtual reality technology provides new solutions, its integration difficulty, cost, and operational complexity constrain its widespread application. This study introduces a digitally twin-based augmented reality (AR) collaborative indoor design framework, addressing the decomposition of spatial planning for the complexity inherent in design processes. Subsequently, contextual data in the indoor design process is structured into an indoor design knowledge graph to elucidate information transmission and iterative mechanisms during collaborative design, thereby enhancing the situational adaptability of AR collaborative design. Utilizing a root anchor-based collaborative approach, multiple designers engage in spatial design collaboration within the AR environment. Real-time knowledge and data facilitated by the design knowledge graph contribute to collaborative decision-making, ensuring the quality and efficiency of collaborative design. Finally, exemplified by a complex interior design project for a commercial space, an AR-based collaborative digital twin (DT) interior design system is established, validating the effectiveness and feasibility of the proposed methodology. Through this approach, designers can preview and modify designs in a virtual environment, ultimately reducing errors, shortening design cycles, lowering costs, and enhancing user satisfaction.**

***Keywords*—Digital twin; optimized design; interior space; multi-person collaborative design**

I. Introduction

In the golden age of commercial building interior design, traditional design concepts are being questioned and new ideas are overturning established principles and paradigms. Commercial buildings, second only to residential buildings in floor area, are the most numerous and widely ranged, touching every aspect of daily urban life [1]. They serve as a window into the socio-economic status of a city, reflecting the material economic life and vibrant cultural character. The interior environment is an essential component of commercial architecture. Analyzing design trends and creating a favorable commercial environment also contributes to urban economic development [2]. Due to the significant costs, long construction cycles, and high public engagement, once completed, commercial interior projects can broadly impact the regional landscape and environment [3]. Consequently, stakeholders demand higher safety, functionality, and economic performance compared to other buildings, leaving no room for error in the design process. However, the interior design industry still faces significant challenges:

1) Interdisciplinary integration and complexity: Interior design involves aesthetics, architecture, environmental psychology, material engineering, and other disciplines. Designers must ensure beauty while guaranteeing functionality and comfort, increasing design complexity. Traditional commercial interior design must consider building types, environmental harmony, landscape coordination, and investment risks.

2) Overreliance on personal experience: Designers' unique styles and experiences mean that designs are often limited by individual capabilities. The lack of standardized design processes leads to inefficiency.

3) Slow feedback and rework: Traditional design processes often require multiple revisions, with each change consuming considerable time and resources, limiting design efficiency.

4) Singular design methods: The complexity of situations hinders the use of precise theories or quantitative methods to demonstrate the scientific aspects of design. Whether it's aesthetics or space and environmental factors, methods for presenting and arguing commercial building interior design solutions are quite singular, urgently requiring a realistic, intuitive, and visual technology method for presentation.

In interior design processes, due to the emphasis on spatial visualization and user experience, the characteristics of virtual reality technology are highly similar, as it is a computer system that presents a virtual world or simulated environment to users. Virtual reality can serve people better by allowing users to experience the architectural environment from all angles and senses from the design's inception. As a result, the integration of interior design with virtual reality technology is gradually being widely applied in the industry.

Firstly, since interior design is a process involving planning, design, and construction, which is costly and irreversible, it cannot afford many errors. Virtual reality technology, with its lifelike presentation, allows for the preview and real-time modification of interior design plans. Designers and users can enter the virtual space at any time, examining their work from any angle, truly feeling the space, scale, materials, textures, details, and sounds, thus resolving issues arising from overlooking errors in two-dimensional design drawings.

Secondly, unlike traditional design media, virtual reality technology describes building interiors dynamically and interactively with real-time feedback. Users can thus compare and edit interior design elements during the preview, modifying them according to their needs and preferences without professional constraints.

In this context, the rapidly developing virtual reality technology facilitates the expression of interactive interior design, enhancing the realism of the experience and meeting the growing demand for "interactivity" among contemporary users.

However, looking at the current application of virtual reality technology in interior design, imperfections in design methodology can cause issues such as how to integrate virtual reality into the design process, resolve the high computational demands and significant costs in terms of capital and time investment, and overcome the lack of familiarity with operating methods limiting its widespread adoption. These issues hinder the digital evolution of architectural interior design methods and the innovative integration and widespread teaching of virtual reality technology in everyday life. Therefore, this paper proposes an augmented reality-driven method for interior space design. This method allows for the examination and evaluation of design effects at the initial conceptual stage, simulating construction quality before building to ensure control, thereby reducing design time and improving design quality while saving resources.

II. Literature Review

In recent years, the rapid advancements in cutting-edge technologies such as artificial intelligence, big data, and cyber-physical systems have been driving the swift evolution of engineering design. This paper provides a comprehensive review of the current state of research in this domain.

A. Digital Design

Currently, digital design technologies have been widely applied in the field of interior space design, particularly in the planning and innovation of residential, commercial, and exhibition spaces [4]. Design software tools such as SketchUp, AutoCAD, and Revit have become indispensable for designers, supporting complex design requirements such as 3D modeling, virtual reality roaming, and environmental simulation. With the development of big data and artificial intelligence technologies, data-driven interior design has become a research hotspot. By collecting and analyzing designers' creative ideas, user behavior data, and the usage effects of interior spaces, more accurate predictions of the functionality and user experience of interior spaces can be made during the design phase.

In recent years, interior designers have intensified their pursuit of rapidly developing interior space design solutions that are both aesthetically pleasing and practical, meeting consumers' demands for personalized and functional interior spaces. Grübel et al. [5] used digital technology to design multifunctional interior spaces that meet strict requirements for environmental adaptability and user interactivity, achieving a level of functionality and aesthetic design comparable to high-end standards. Lu et al. [6], focusing on home office spaces, explored the application of digital design and analysis technologies in interior space design, combining digital design with user behavior analysis to achieve optimal design outcomes. Künz et al. [7] summarized the development of some advanced digital interior design methods, particularly emphasizing advanced digital design for smart home products beyond traditional furniture and decorative materials. This approach is considered key to improving residents' quality of life fundamentally. Schroeder et al. [8], utilizing digital technology, proposed a data-driven intelligent interior design simulation model based on user experience feature learning. Using personalized design techniques and leveraging user behavior data and spatial layout data, they designed personalized interior environments.

However, as user demands for interior spaces become increasingly personalized and functional, new challenges arise for digital interior space design. How to rapidly design interior spaces that meet specific user needs while ensuring design feasibility and sustainability is a major research direction in the future of digital interior space design.

B. DT-driven Design Patterns

DT technology has been widely applied throughout the entire lifecycle of interior space design, construction, and maintenance. For instance, Coupry et al. [9] designed an interior design visualization technology based on DTs and virtual reality. This system provides an intuitive representation and accurate description of interior space layouts, systematically manages spatial usage data and user interaction data, thereby enhancing design precision. Schott et al. [10] proposed a DT-driven interior design collaboration platform, establishing a stable and reliable communication mode among designers, engineers, and clients throughout the entire design process.

In response, Zhu et al. [11] introduced a comprehensive, precise, real-time interior environment monitoring and analysis system. This technology, by bridging the gap between the actual interior environment and the digital model, enables real-time iteration and optimization of interior design. As interior space design becomes increasingly complex, requiring knowledge from multiple disciplines, Xu et al. [12] identified DT (DT) as one of the most promising enabling technologies for achieving smart buildings and smart cities. Therefore, integrating knowledge from different disciplines in the design process to realize interdisciplinary digital interior space design is a crucial future research trend.

In light of this, Pang et al. [13] proposed a DT-driven method for rapid personalized design of residential and commercial spaces. Wang et al. [14] presented a rapid personalized design method for office space layouts based on DTs. They developed an analysis-decoupling framework based on DTs to provide interior design analysis capabilities and support decision-making for design and solution assessment. Liu, Zheng & Bao [15] discussed the application of DT models as a natural evolution in model-based engineering in interior design. These are important application cases of DTs in the interior space design phase. The application of DT-driven interior space design has been summarized by relevant scholars and proven to be a significant method for enhancing the interior design process. DT technology holds greater efficiency potential in the construction and management of interior spaces.

C. Research Gaps

With the evolution of modern interior design, spatial planning and personalized customization have become increasingly intricate and detailed, posing challenges that current design methods often struggle to address. Despite the ongoing shift of contemporary interior design methods towards three-dimensional modeling and virtual reality technologies, inherent issues persist, as outlined below.

1) Lack of parameterized collaborative design approaches: This implies that manual adjustments are required when spatial functional needs or user preferences change, leading not only to time consumption but also potential design inconsistencies. Introducing parameterized collaborative design approaches can automate design adjustments, saving time and enhancing design consistency and accuracy.

2) Application of DTs in the design process: Furthermore, although DTs have found widespread applications in various domains such as manufacturing and medical simulation, their application in the interior design process remains underexplored. DTs can provide additional information for the design process, including spatial usage simulation, lighting, and acoustic effects, thereby elevating design precision and user satisfaction.

Motivated by these identified research gaps and objectives, this study aims to develop a DT-based intelligent collaborative design method for interior space design. Integrating parameterized collaborative design and DT technology, this approach seeks to enhance the efficiency, precision, and personalization of interior space design. Simultaneously, this research aspires to propel the advancement of interior design by presenting innovative perspectives and methodologies for future endeavors in this field.

III. DT-BASED MULTI-PERSON COLLABORATIVE DESIGN SYSTEM

To meet the application demands of intricate assembly scenarios, this chapter delves into the intricacies of collaborative scenarios. It introduces an architecture for multi-user collaborative assembly methods based on Augmented Reality (AR) and DT technology. Additionally, it conducts an analysis of collaborative assembly sequences within the DT framework.

A. Multi-Person Collaborative Design Process

In intricate interior space design, the design process typically encompasses multiple complex stages, demanding precision in design execution and necessitating close coordination between these stages. Collaborative design involving multiple individuals can significantly enhance design efficiency, contingent upon efficient task collaboration. The collaborative process relies on the macro-management and swift allocation of tasks by the design administrator. Simultaneously, it is constrained by the understanding of tasks by on-site design personnel and the execution of design operations. Fig. 1 illustrates the collaborative process of complex interior space design. This paper divides the collaborative design process into two parts: single-functional area design collaboration and multi-functional area design collaboration.

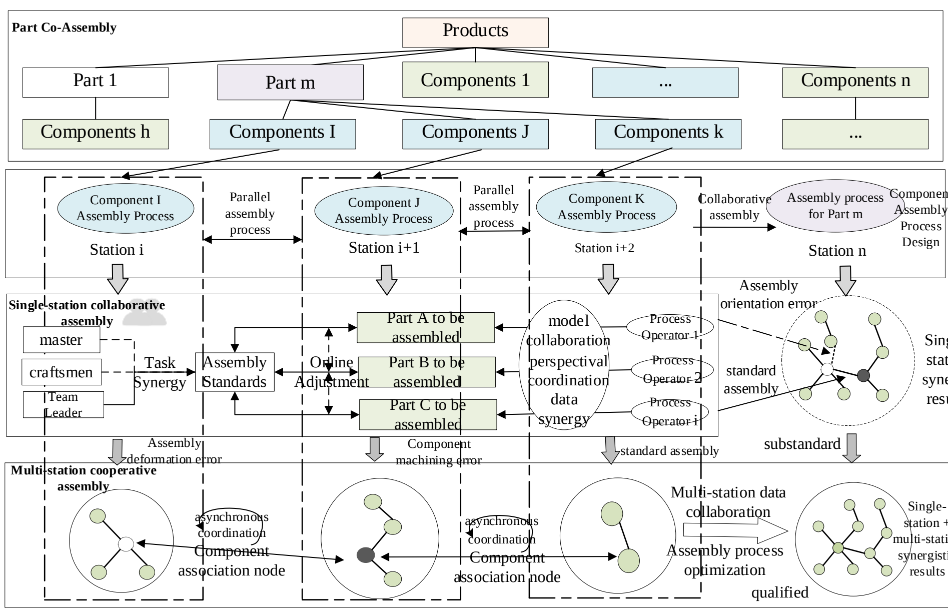

Fig. 1. Collaborative process for designing complex interior spaces.

1) Complex interior space design process in a single functional area: When the design requirements of a space are complex, multiple designers conduct different design operations in the same functional area from different design perspectives. This task collaboration process is termed single-functional area collaborative design. In this design process, senior designers are responsible for formulating design concepts, design managers review design proposals, design task cards are created based on the design process, project managers manage on-site activities, guide and plan the work of designers, and collaborative designers' complete tasks. The collaborative process primarily focuses on the interaction between project managers and designers, with the project manager being the key decision-maker in collaboration. During the design process, rapid extraction of individual design tasks and collaborative relationships, along with unified and accurate acquisition and expression of information, is crucial for on-site designers to effectively grasp design details. Additionally, due to the tolerance range in design quality standards, it is necessary to systematically coordinate, optimize design parameters based on on-site conditions, and iteratively control the design process to ensure the stability of collaborative design quality.

2) Collaborative design process for complex interior space with multiple functional areas: When the tolerance requirements for space design are high, and there are multiple and interrelated functional areas, not only must design integration errors arising from the collaborative design process between various functional areas be considered, but also the cumulative errors resulting from material selection, furniture layout, and lighting design errors in the design processes of each functional area leading to design inconsistencies. The design process is top-down, controlling from overall design concepts to specific design elements. It macroscopically manages the design process and, based on the relationships and design precision of various functional areas, optimizes the design process into a multi-functional area collaborative design process. Due to the independence of each functional area, information collaboration computation and feedback between functional areas are crucial means to achieve accuracy prediction and process optimization.

B. Multi-person Collaborative Design Approach Incorporating AR

In order to ensure the efficiency of interior space design, this paper optimizes the collaborative design process and establishes a DT-based AR multi-user collaborative design architecture, as depicted in Fig. 2. Within the DT space, the three-dimensional model and design information are initially processed to extract abstract design attribute information and relational information, which is employed for the expression of design knowledge. Subsequently, design semantic information is organized in the format of "Entity-Relation-Entity" and "Entity-Attribute-Value" to construct a design knowledge graph. Object mapping is conducted based on the knowledge graph to build the design twin. Each node in the knowledge graph represents the twin representation of a physical object in the digital space. Based on hierarchy, these representations are categorized into object-level twins and space-level twins. The latter includes both attribute and layout information. The DT serves as the foundation for design management and data collaboration.

The AR-guided scenario serves as a bridge between the physical design space and the DT design space, facilitating guidance and collaboration throughout the design process. The AR system disseminates and visualizes designers' tasks based on the collaborative attribute information of nodes in the design knowledge graph, constructing a collaborative AR space. Model collaboration, perspective coordination, and data collaboration in single-functional area collaboration are achieved through multi-device collaboration and control.

The physical design space acquires design and collaborative information through the AR system, completing collaborative design tasks with visual guidance. To guide different collaborative tasks, the AR system possesses independence and collaboration. Independence ensures the guidance of different design tasks for various functional areas, ensuring effective guidance for single-functional area collaboration. Collaboration involves self-adjustment based on the design conditions of other functional areas during multi-functional area collaboration, ensuring that the overall spatial design meets aesthetic and functional specifications.

The DT space guides the design implementation of the physical space based on design principles, ensuring the standardization and efficiency of the design process through the virtual-to-real mapping process. Changes in the physical space's design drive the evolution of the DT, ensuring the high fidelity of the DT design process through a bidirectional mapping approach.

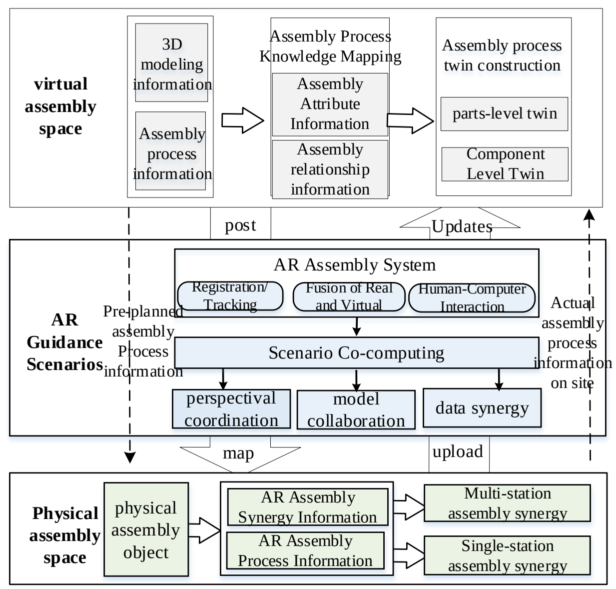

Fig. 2. DT-based multi-person collaborative design architecture for AR.

IV. DT-Driven Linked Design Process

This section provides a DT-driven approach to multi-person collaboration.

A. Process Collaboration

In this section, we employ manufacturing processes as fundamental units to establish an augmented reality-based DT multi-user collaborative interior space design workflow, as illustrated in Fig. 3. The process delineates the transmission and iterative mechanisms of design information between the physical design scenario and the DT space.

In the figure, following the determination of the interior space design scheme, the twin space stores and expresses design information in the form of a knowledge graph, where nodes represent specific design elements, and edges signify relationships between design elements. Each node in the interior design knowledge graph corresponds to a DT of interior elements or functional zones, serving as an abstract representation of physical objects. The entire knowledge network is capable of describing the entire interior design scheme. The AR system, based on the interior design knowledge graph, can acquire the Design Element Set (DES) for the entire design process. DES is the knowledge expression of the pre-planned design scheme, i.e.

$$DES = \sum_{i=1}^{n}(SAI_i \cup DPI_i \cup DCI_i) \quad (1)$$

where, DES is used for modularized management of the interior space design process. It comprises Scene Asset Information (SAI) for AR scene reconstruction, Design Planning Information (DPI), and Design Cooperation Information (DCI) for design guidance and collaborative processes.

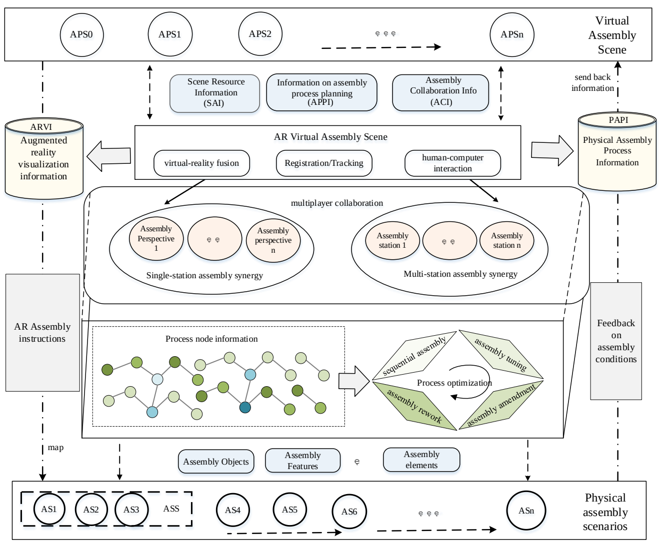

Fig. 3. DT interior space design process collaboration.

Due to the complexity of the interior design processes, we decompose them into various design step combinations for different categories of AR collaborative guidance. Different Design Element Sets (DES) are composed of Design Step Sets (DSS). Designers acquire the corresponding DSS through the system to obtain information on design steps, requirements, features, and elements. Based on specific design tasks, we classify them into two design cooperation categories (DCC): single-functional zone design and multi-functional zone collaborative design. The AR system provides distinct collaborative guidance for different DCC, generating Augmented Reality View Information (ARVI) based on design and model information, formally expressed as

$$ARVI := \{UI \cup MBD \cup ADN\} \quad (2)$$

The Model-Based Definition (MBD) method is employed for AR display of model information in Scene Asset Information (SAI), Design Animation (ADN) for visual expression of Design Planning Information (DPI), and UI information for expressing Design Cooperation Information (DCI) and design property information. Designers implement design steps based on ARVI to advance the DSS process. During the execution of DSS in physical space, the system acquires Physics Design Information (PDI), including Material Information (MI), Design Process Data (DPD), and Design Adjustment Data (DAD), formally expressed as,

$$PDI := \{MI \cup DPD \cup DAD\} \quad (3)$$

PDI is directly fed back to the interior design knowledge graph through human-computer interaction. Through analysis and computation, the system predicts the current state of the design process twin object and performs distributed optimization based on this state. Firstly, DES is optimized, adjusting errors to different degrees based on the actual design situation, facilitating differential optimization processes such as design adjustments, corrections, or rework. Design adjustments mainly address design errors in single-functional zones, while design corrections and rework address overall aesthetics and functionality matching issues in the collaborative processes of multi-functional zones. DCI updates involve the optimization results communicated through the AR system, guiding designers through the UI for process optimization and error indication.

B. Scene Synergy

One primary feature of AR systems is the overlay of computer-generated three-dimensional graphics onto physical space to provide operational guidance, fulfilling a majority of instructional needs. However, in scenarios involving multiple operators, independent AR spaces are incapable of facilitating information sharing and interactive operations. In order to overcome information isolation and enable multi-user collaborative operations, this paper introduces a shared AR space constructed through the method of root anchor point alignment, achieving collaborative scene interactions.

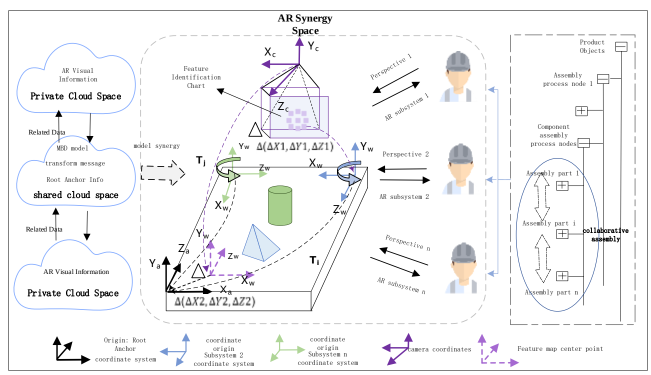

Fig. 4. Scenario collaboration principle.

The AR collaborative system for interior design enables multiple designers to share and collaborate on design concepts within the same physical space. As illustrated in Fig. 4, during the interior design process, designers collaborate by creating their respective AR spaces. Each designer's AR device establishes a unique world coordinate system, with the root anchor point serving as the origin (0, 0, 0) for the coordinate system, and all design element models are loaded as child objects.

The key to establishing a unified coordinate system is aligning the root anchor points of multiple virtual scenes. In this section, the collaborative process is achieved by calculating relative coordinate offsets based on the overlap point of the physical spaces of two devices. Image-based tracking technology is employed to determine the location information of common points in physical space. To simplify collaborative calculations and enhance system adaptability, feature recognition images are stored in the system. The relative coordinates of the feature recognition image with respect to the root anchor point are utilized for rapid acquisition of common coordinate points between devices through screen recognition of the feature image. These relative coordinates are then employed in the alignment calculation of the root anchor points of the two devices, achieving a unified coordinate system.

Initially, the benchmark device DS for collaborative calibration is determined. Since the camera is in a non-fixed state during the AR scene loading process, the camera coordinates V_{ecp}（X_P，Y_P，Z_P） at the calibration moment are obtained as the central coordinates of the feature recognition image. Considering the camera offset constants for different devices, the actual central coordinates of the feature recognition image are adjusted to V_{ecp}（$X_P+\Delta X_1$，$Y_P+\Delta Y_1$，$Z_P+\Delta Z_1$）. To align the root anchor points, the local coordinates relative to the feature recognition image are computed as the coordinate offset, taking into account the coordinate transformation rules of the virtual space. The matrix transformation sequence in its coordinate system involves the Y-axis, then the X-axis, and finally the Z-axis. Thus, based on the transformation rules, the world coordinate system W is transformed to the local coordinate system L, where a and b represent intermediate coordinate systems in the transformation process.

$$Rot_W^L = Rot_{\mathrm{b}}^L Rot_{\mathrm{a}}^{\mathrm{b}} Rot_W^{\mathrm{a}} \tag{4}$$

The local coordinates of the root anchor point under the feature recognition image are obtained through matrix operations as V_{eca}（ΔX_2，$\Delta Y_2, \Delta Z_2$）.

$$V_{eca}{=}R_W^L \mathrm{Tr}\left(X_P+\Delta X_1\ ,\ Y_P+\Delta Y_1\ ,\ Z_P+\Delta Z_1\right) V_{ecp} \tag{5}$$

During device calibration, the client utilizes AR Core image tracking technology to obtain the spatial coordinates V_{ect}（X_t，Y_t, Z_t） of the recognition image through feature point clouds. Since the offset of the recognized feature point cloud may introduce deviations in calibration results, a collaborative filtering method is employed to eliminate false coordinates caused by positioning offset. Additionally, the data is grouped, and a weighted arithmetic mean is calculated.

$$X' = \frac{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{x_i f_i}}{\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{f_i}} = \frac{\mathrm{x_1 f_1 + x_2 f_2 + \cdots + x_n f_n}}{\mathrm{f_1 + f_2 + \cdots + f_n}} \tag{6}$$

Get the final coordinate values of the feature recognition map.

$$V_{ect}{=}\left(\ X_t'\ ,\ Y_t', Z_t'\ \right) \tag{7}$$

Due to the identical screen coordinates of the two devices, a unified coordinate system can be achieved by determining the same coordinate offset. The client's root anchor point is transformed into the local coordinate system of the feature image, setting the same coordinate offset V_{eca}. Based on the existing coordinate offset and the spatial coordinates of the feature recognition image with rotation angles V_{ecr}（θ_1，θ_2，θ_3）, the root anchor point coordinates are aligned in the world coordinate system. According to the matrix transformation rules in the world system, the transformation matrix for the root anchor point is obtained by rotating in the z-x-y sequence.

$$R_L^W = Rot(Y,\theta_2)\, Rot(\mathrm{X},\theta_1)\, Rot(\mathrm{Z},\theta_3) \tag{8}$$

Get the coordinates of the root anchor point in the world coordinate system.

$$V_{eca2}{=}Tr\left(X_t'\ ,\ Y_t'\ ,\ Z_t'\right) R_L^W V_{eca} \tag{9}$$

In the equations, $Rot(x,\theta) = \begin{bmatrix} M(x,\theta) & 0 \\ 0 & 1 \end{bmatrix}$ represents a rotation matrix, where $M(k,\theta) = I + \sin\theta R_{\vec{k}} + (1-\cos\theta) R_{\vec{k}}^2$ is the rotation matrix for any vector $\vec{k}$ rotating counterclockwise around the axis by an angle θ in three-dimensional space. Here, I is the 3×3 identity matrix, and $R_{\vec{k}}$ is the cross-product matrix of $\vec{k}$.

$Tr(x,y,z){=}\begin{bmatrix} I & (x,y,z)^{\mathrm{T}} \\ 0 & I \end{bmatrix}$ denotes the translation matrix.

After spatial calibration of different devices, although the root anchor points in each AR space have different numerical values in the world coordinate system, they are aligned in physical space, serving as the origin of the shared AR space's common coordinate system. In the shared coordinate system, AR resources only need to exist as their child objects and ensure local coordinate consistency to achieve spatial coordinate collaboration.

Scene collaboration involves both coordinate collaboration of the shared AR subsystem and collaboration of AR resources. Building on the foundation of root anchor-based coordinate collaboration to construct a shared AR space, a unified loading of AR resources and consistency in resource interaction can be achieved under different assembly perspectives. Collaborative resources are stored in shared cloud storage, and when the MBD model is stored in the shared space, the creation of the AR scene in a procedural form ensures consistency in model loading and removal, monitored through the shared space. In achieving consistency in the interaction process, as transformation information (transform) stores the basic attributes of resources, the system monitors and updates it in real-time to ensure consistency in model interactions, such as movement, rotation, and scaling operations in different spaces.

Through AR scene collaboration, operators can perform assembly based on collaborative perspectives, and the natural AR human-computer interaction ensures effective transmission of collaborative information.

V. CASE STUDY

This paper develops an augmented reality-based multi-user collaborative design system using the aforementioned approach and validates it through a case study of an interior design project.

A. Platform Construction

The establishment of the interior space design management platform primarily aims to provide data services for the design process, encompassing information storage and expression of interior design elements, definition and storage of augmented reality (AR) resources, and integration of collaborative design algorithm services. Firstly, a knowledge graph of interior design is constructed based on the spatial design requirements. This involves utilizing the DT and spatial relationships of design objects to obtain design precision information and design relationships for design nodes. Subsequently, design errors are calculated, facilitating the iterative update of on-site design information.

The design-level DT manages the fundamental information of interior design, while the object-level DT oversees its basic attribute information. The knowledge representation of the interior design DT is illustrated in Fig. 5, encompassing attribute information such as augmented reality (AR) visualization and algorithmic interfaces. The visualization information primarily includes interior design object models and information on interior design elements. Simultaneously, the algorithmic interfaces furnish collaborative design algorithms utilized in the collaborative calculation processes of design.

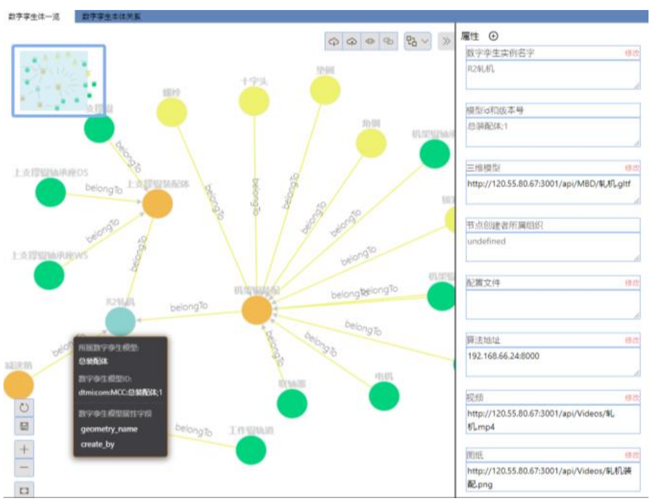

Fig. 5. Interior design DT knowledge expression.

In response to diverse on-site design requirements, the Augmented Reality (AR) system leverages the DT platform to acquire resources, establishing an adaptive AR design environment. Through real-time rendering and AR visualization of design elements, parameters, and tools, the system guides designers in the creative process, thereby reducing cognitive load and enhancing design efficiency.

B. Test Validation

Incorporating Augmented Reality (AR) technology into interior space design can enhance both design efficiency and customer experience. This study explores collaborative work modes in the interior design process by combining smartphones and HoloLens headsets. Using a smartphone as the collaborative reference platform, coupled with Vuforia image tracking technology, synchronization of root anchor points between HoloLens and smartphones within the same AR space is achieved. To enhance the precision of collaboration, recognition images with distinct features are chosen, and stability tests for rotation and scaling are conducted. The collaborative accuracy primarily relies on the alignment of root anchor points across different devices. This is indirectly measured by sending the physical dimensions of the recognition image to each collaborative device and comparing the results with the image tracking outcomes.

Fig. 6. Root anchor synergy process.

As illustrated in Fig. 6, this process accurately tracks the positions of interior design elements under different sizes, distances, and rotation angles. It achieves precise alignment with translation errors approximately 1mm and rotation errors less than 0.5 degrees, providing a reliable reference for the collaborative interior design process. Fig. 6 presents the visual effects of the collaborative interior design scene from different perspectives, namely the smartphone AR perspective and the HoloLens AR perspective. Within the AR collaborative space, design elements are categorized into private information, public information, and associated information. For instance, foundational elements of the design, such as major furniture or structural components, serve as public resources shared by all participants, ensuring consistency in physical space and interactive effects from different perspectives.

Private information is tailored to the specific tasks of individual designers. Different designers may see different AR elements based on their task requirements. Key design objects, like specific furniture or decorative elements, although requiring attention from all designers, may have different details of interest to each designer. By setting element attributes as private, designers can interactively translate and rotate models to comprehensively understand and examine every angle of the design objects.

C. Physical Assembly Process Synergy

This section analyzes the collaborative effects of the physical design process through an on-site interior design implementation experiment. Designers arrived at the actual interior design site and engaged in collaborative design layout activities for the central area of the living room. Given the diverse design objects and the complexity of the design environment, acquiring on-site information proved challenging for the designers. To address this challenge, designers accessed design element information, including collaborative design tasks and design resources, through the tethering of the DT design platform to assist in the design process. Designers were then able to visualize three-dimensional models and drawings of the design resources using augmented reality (AR).

The collaborative layout design of the central area requires the joint efforts of multiple individuals. During the design preparation phase, designers, designated as A, B, and C, gather design information from various visual perspectives based on their respective roles and responsibilities. It is displayed the AR visual perspectives of designers A, B, and C. Designer A is responsible for overall concept confirmation and design optimization, primarily assisting in layout design. To facilitate effective design guidance, the AR system visualizes the design baseline for this perspective, allowing designer A to comprehend the structural model of the spatial layout. To achieve task collaboration among designers, different forms of visualization for resources are necessary. Since all designers use the central area model as the baseline for their designs, with its attributes set as "Public" for shared visualization, designers B and C can observe the spatial model loaded by designer A in the shared AR space, enabling task collaboration. Designer B, acting as the lead designer, is tasked with central area layout design. The AR system employs design animation to demonstrate layout details, guide the design process, and visualize the effects. Designer C's task is to test the layout's effectiveness and assist in the design process. The system uses Model-Based Definition (MBD) model visualization to help designer C obtain design parameter information. To avoid interference caused by the overlay of visual resources from multiple AR subsystems, the model attributes of the central area are set as "Private," visible only to designer C. Interactions by designer C with the central area do not affect the design animation presentation for designer B

Throughout the entire design process, designers can iteratively update design solutions by uploading real-time design information to the DT space through AR system interactions such as voice commands or gestures. The optimized information is then fed back to the design team via the AR system, completing a closed-loop control of the design.

To validate collaborative design efficiency, designers responsible for other design elements were divided into two groups and subjected to 20 experiments each. The parameters, including design preparation, completion, and documentation, were compared with those of experienced designers focusing on the central area, as summarized in Table I.

TABLE I. COMPARISON OF ASSEMBLY EFFICIENCY FOR DIFFERENT ASSEMBLY CATEGORIES

Assembly category	Preparedness efficiency	Assembly Fluency	Assembly Collaboration Efficiency	Assembly Special Session Completion	Assembly pass rate	Assembly completion efficiency	Assembly process record efficiency
Senior Designer Codesign	100	100	100	100	100	100	100
New Designer Codesign	45	45	40	80	65	30	70
New Designer Codesign	90	80	85	100	95	85	160

From Table I, the following observations can be made: ① New designers utilizing traditional processes and methods for interior design tasks incurred substantial time in design preparation and documentation. Although the design qualification rate exceeded 50%, the design efficiency fell short of meeting the scene's requirements. ② AR-based collaborative design, supported by DTs and AR technology, exhibited overall favorable performance. ③ In the AR collaborative environment, the design collaboration efficiency of new designers was twice that of traditional design, enabling the new team to quickly adapt. ④ Guided and alerted by AR, designers were less prone to overlook design aspects, achieving a 100% completion rate for handling detailed elements in spatial layouts. The overall design qualification rate reached 95%, ensuring the stability of design quality. ⑤ AR's data interaction eliminated communication barriers between physical space and the twin space, and the efficiency of recording design information in the design process even surpassed that of experienced designers. In comparison, it is evident that AR-guided collaborative design based on DTs significantly reduces the cognitive burden on designers and enhances both the stability of design quality and overall design efficiency.

D. Analysis and Discussion

In the digitized process of interior space design, interactive experience and efficiency are crucial considerations. Within the digital design environment, a well-crafted interactive experience significantly impacts the work efficiency of designers and the quality of design outcomes. The user interface of design software should be intuitive, easy to understand, and flexible enough to adapt to the designer's workflow. Efficiency is equally vital in the digital design of interior spaces. The design process should be swift, flexible, and capable of adapting to evolving customer demands and market trends.

Through the experiments described above, the proposed method and developed system demonstrate the following advantages in terms of interactive experience and design efficiency:

1) The design software provides real-time views of spatial models, allowing designers to immediately see how their design choices impact the layout and aesthetic effects of the space. Simultaneously, the software enables designers to effortlessly adjust design parameters and instantly observe the results of these adjustments. This immediate feedback significantly enhances design efficiency and quality. Furthermore, the design software supports seamless integration with other tools and platforms, such as VR/AR demonstration software, material databases, and 3D printing systems. This facilitates a smoother design process, reducing waiting and conversion times.

2) The software allows for the rapid creation of initial 3D models and 2D floor plans for interior layouts, saving time. While some designs may require adjustments to existing models, at least one-third of the projects need a complete redesign. For instance, forming a preliminary design model in 15 minutes contrasts sharply with the days or even a whole day required for a seasoned designer to conceptualize a design from scratch or make adjustments to an existing model. This results in substantial savings in design costs.

In conclusion, this system provides robust tools for the digitization of interior space design, enhancing both design efficiency and quality while optimizing the user's interactive experience to meet the rapidly changing demands of the market.

VI. Conclusions and Future Work

This research investigates the current status and challenges within the interior space design industry, proposing an intelligent design approach based on DT. We identify interdisciplinary integration challenges in the design process, limitations associated with design knowledge relying on personal experience, and issues stemming from frequent design modifications, lengthy project cycles, and high work intensity imposed by traditional design patterns. To address these challenges, we establish multi-physical information models for interior spaces, systematically describing rule models for design knowledge and experience in a digitized format. Additionally, we achieve intelligent parametric design associations among spatial elements.

This design approach not only enhances design efficiency and quality but also opens new avenues for the intelligence of interior space design. In the future, we aim to refine this design approach, improving the accuracy and reliability of the models, enhancing the intelligence of rule models, strengthening the intelligent parametric design associations among spatial elements, and exploring the application of this method in a broader spectrum of interior design domains. We will also investigate the integration of this design method with advanced digital technologies, such as artificial intelligence and big data, to achieve a higher level of intelligent design.

The primary contribution of this research lies in the proposal and implementation of an innovative interior space design method, with the potential to drive the transformation of the design industry towards intelligence.

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