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Computer-Aided Design AND APPLICATIONS

Virtual Reality System of Ceramic Design Integrating Multi-Modal Perception and Implementation Algorithm

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Abstract. The aim of this study is to devise a VR system for ceramic design that combines multi-modal perception with CAD technology, aiming to enhance design efficiency and user satisfaction. We offer designers a novel immersive platform by creating an ultra-realistic 3D design setting, integrating various sensory inputs like sight, sound, and touch, and seamlessly interfacing with CAD data. Experimental findings reveal that, in contrast to an unimodal design setting, designers using our system decrease task completion time by an average of 65%. Additionally, the creativity and practicality of their designs have notably improved. Our system notably boosts designers' productivity and elevates the user experience in ceramic design. This introduces cutting-edge design tools and methods to the ceramic industry and explores the vast potential of VR technology in this domain, thus infusing new life into the industry's innovation and progress.

Keywords: Ceramic Design; Virtual Reality; Multi-Modal Perception; Computer-Aided Design; Design Efficiency
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1 INTRODUCTION

Ceramic design, as a part of China's traditional craft, has a long history and profound cultural heritage. However, in modern society, the ceramic design industry is facing many challenges. Regarding the application of virtual reality (VR) in the design and development of ceramic products, despite its enormous potential, related research and practice have always shown a relatively scattered and scattered state. These sources cover multiple aspects of VR technology in ceramic product design, including supported design functions, adopted VR technology, and complementary applications combined with other systems. Especially in terms of how virtual reality technology effectively supports the early design stage of ceramic products and its practical application in the creative design stage, the discussion is still not in-depth and comprehensive enough. In order to gain a more systematic understanding of the application of VR in ceramic product design, Berni and

Borgianni [1] reviewed relevant literature and conducted a detailed classification and analysis of 65 sources. The defect detection of daily ceramic bowls is mostly still limited to traditional detection methods. It's low detection efficiency and high labour intensity have become major criticisms. There are relatively few testing equipment for daily ceramics on the market, mainly due to the high cost of testing equipment and the diverse types of daily ceramics, which are not conducive to equipment development. Meanwhile, prolonged and high-intensity manual testing is bound to lead to the occurrence of product false positives, missed detections, and other phenomena. Burghardt et al. [2] developed an online detection system for circular daily ceramics, which includes a production line simulation system and an intelligent control system. It has developed intelligent detection software, which includes typical defect detection algorithms for daily ceramics such as roundness, notches, patterns out of bounds, cracks, and slag drops. Then transfer the image to the upper computer, perform algorithm detection on the image, and transmit instructions to display the detection results of the workpiece. And display the detection results on the interface designed by LABVIEW. It has built a hardware pipeline platform, which uses automatic conveyor belts to transport products to appropriate positions, triggering photoelectric sensors to send signals and collect images. VR technology is also known as virtual reality technology. Recently, with the rapid development and popularization of VR technology, VR displays have been widely used in various fields of projects and products. Ceramic works generally consist of three basic elements: ceramic material, shape, and decoration, with dual cultural characteristics of material and spirit. Cai et al. [3] constructed a highly immersive and interactive virtual ceramic VR display game system. By combining VR technology with ceramic culture, people can rediscover the meaning of ceramic culture, love life, and pursue happiness, harmony, and auspiciousness in a virtual "real" environment. It introduces the background and significance of ceramic VR display games, as well as the commonly used VR technologies Unity3D and VR technology. According to the system design, develop a ceramic VR display game, including finalizing game original drawings, game modelling and textures, interactive implementation, and game engine import. Users can use various methods such as downloading Android, iOS, and PC versions for VR browsing, which can save them a lot of costs. Showcasing the background with ceramics, using 3D modelling and VRTK plugin processing software to jointly develop, allowing people to understand ceramics while watching and playing. Simultaneously promoting the development and application of VR technology, promoting Jiangxi ceramic culture, and promoting traditional Chinese culture.

As a new technical means, VR technology shows a broad application prospect in the field of design with its immersive interactive experience and intuitive design presentation. The 3D printing technology of ceramic materials based on extrusion-free forming (EFF) is an important branch in the field of additive manufacturing. When exploring the effect of solid content on the rheological behaviour of Al $_2$ O æ ceramic slurry, Chen et al. [4] conducted an in-depth analysis of the correlation between solid content, slurry viscosity, and flowability. They conducted a systematic study on the influence of sintering temperature on the microstructure and accuracy of 3D printed parts. However, excessive sintering temperature can cause ceramic particles to transform into a liquid phase, which not only affects the shape and size accuracy of the sintered sample but also may cause thermal expansion and deformation of the material. Meanwhile, the sintering process at high temperatures also helps to reduce cracks and pores in ceramic components, thereby improving their overall performance. As the sintering temperature gradually increases, the ceramic particles in the green body begin to undergo solid-state sintering, and the gaps between the particles gradually decrease, making the green body more dense. Through VR technology, designers can create a three-dimensional and realistic virtual environment, which can not only improve the design efficiency but also predict the effect of the final product at the early stage of design, thus greatly reducing the design risk. Ceramic design plays a crucial role in modern architecture and interior design. However, although biomimetic methods provide new ideas for ceramic design, existing biomimetic methods often lack sustainability considerations. The response behaviour of ceramic design in buildings has attracted widespread attention. Some innovative methods, such as adaptive design and biomimetic envelope, have made significant progress in this regard. While pursuing biomimetic effects, we should not overlook the efficient utilization of resources, energy conservation, and environmental protection. Through an in-depth analysis of construction and related research over the past five years, Del et al. [5] understood the connection between ceramic material selection and manufacturing and explored how to achieve sustainability in biomimetic design.

In the process of ceramic design and testing, users often need to interact with physical materials to obtain more realistic and intuitive feedback. Especially in the field of ceramic design and testing, VR technology can not only provide designers and testers with new ways of working and perspectives but also greatly improve design efficiency and quality. Therefore, Fouad et al. [6] envisioned enhancing user perception and understanding of virtual ceramic materials by introducing physical props in VR environments, such as tactile gloves that simulate ceramic texture, force feedback devices that can simulate ceramic weight, etc. In VR environments, users can form unique experiences and memories by interacting with virtual ceramic props. It explores the impact mechanism of ceramic props in virtual experiences on user memory retention and how to improve user memory retention by optimizing the design of VR environments. Accurate prediction of material properties is crucial for ensuring the stability of product performance and quality in the process of ceramic product design. Frutiger et al. [7] proposed an optimization strategy based on the Monte Carlo method to solve computer-aided molecular design (CAMD) and process design model problems considering fluid property uncertainty. Therefore, carrying out effective process design under property uncertainty has become an important challenge faced by the ceramic industry. Through this approach, they can more accurately evaluate the uncertainty of the prediction model and develop more reasonable process design plans based on it. However, in practical applications, the prediction of material properties often faces uncertainty, especially in predicting fluid properties. In the process of applying this method to ceramic product process design, they can first determine the required material properties and establish corresponding GC prediction models. Ceramic making in technical education has always been regarded as an effective way to cultivate students' hands-on and innovative abilities. Guan et al. [8] applied a virtual reality-based ceramic production method to technical education in a junior high school with the aim of examining the impact of this new method on student creativity and learning engagement. Through VR devices, students can simulate the real process of pottery making. In a typical pottery class, the teacher first teaches students the basic techniques and theories of pottery and then gives them the opportunity to practice, allowing them to make pottery works themselves. Through pottery making, students can not only learn traditional craft skills but also exercise their imagination and creativity in the creative process. With the introduction of multi-modal sensing technology, VR systems can more truly simulate human perception in the real world. By combining visual, auditory, and tactile modes, designers can get more comprehensive design feedback in a virtual environment. At the same time, as an important tool of modern design, CAD technology provides great convenience for ceramic design with its accurate numerical representation and powerful editing function.

The system provides users with a brand-new immersive design experience through the fusion of a highly realistic three-dimensional design environment and multi-modal perception. User feedback shows that this experience makes the design process more interesting and efficient and greatly optimizes the user experience.

The system realizes a seamless connection with CAD data, which enables designers to operate CAD models in a virtual environment directly. This innovative function breaks the boundary between traditional design and VR and provides designers with greater flexibility and convenience.

The core content of this study is to develop a ceramic design VR system that integrates multi-modal perception and CAD technology and study its implementation algorithm. Specific objectives include: (1) Building a realistic virtual environment for ceramic design; (2) Realizing the comprehensive integration of multimodal perception; (3) Seamless integration of CAD technology into the VR system; (4) The practicability of the system is verified by simulation experiments. In order to achieve the above goals, this study will adopt the following research methods and article arrangements: (1) In-depth study of the related theories and implementation methods of VR, multimodal perception and CAD technology; (2) Design and develop a prototype of ceramic design VR system; (3) Continuously optimize the system performance and user experience through user testing and simulation experiments; (4) Summarize the research results to provide strong support for the innovation and growth of ceramic industry.

2 RELATED WORK

Hanssen [9] delves into how new technologies can promote the development of ceramic art on the basis of inheriting the essence of traditional ceramic technology. Through virtual reality (VR) technology, craftsmen can simulate the real throwing process in the digital world. Specifically, this paper provides a detailed analysis of how Oculus Rift and clay 3D printing technology are combined with traditional techniques for throwing vessels in ceramic handicrafts. By integrating the process of throwing and pattern making, craftsmen can design and create patterns while constructing throwing objects. This innovative method not only simplifies the process flow but also allows the work to integrate more modern elements and creativity while maintaining traditional craftsmanship quality. The development process of ceramic products involves multiple stages, including requirement analysis, conceptual design, detailed design, production preparation, and subsequent product evaluation. In ceramic product design, the integration and application of design knowledge are crucial for improving design quality. CAD technology, with its powerful 3D modelling and simulation capabilities, is playing an increasingly important role in ceramic product design. By combining specific 3D CAD software, designers can design products more intuitively and efficiently. Not only did it analyze the basic applications of CAD technology in ceramic product design, such as modelling, rendering, etc. Through an in-depth analysis of the development process of ceramic products, Liu [10] proposed a ceramic product configuration editor based on 3D visualization interface software. And successfully integrated it with the Product Data Management System (PDM) to form a complete software system for ceramic product development. This system not only improves the efficiency of ceramic product design but also optimizes the entire product development process. The introduction of virtual reality (VR) technology has undoubtedly brought revolutionary changes to the preservation and restoration of ancient ceramics. However, traditional preservation and restoration methods are often limited by technical conditions and human factors, making it difficult to preserve the original appearance and details of ancient ceramics fully. As a precious cultural heritage carrying rich historical information and artistic value, the preservation and restoration of ancient ceramics have always been of great concern. Firstly, existing VR applications often lack systematicity and user orientation, making it difficult for users to get started and effectively use them [11] quickly.

Augmented reality (AR), as an advanced technology that has emerged in recent years, has a development prospect that is closely related to the widespread application of 5G networks. Morín et al.'s [12] research delve into the integration of distributed AR implementation and 5G network technology. Mor í n et al. emphasized that 5G technology and its ecosystem are crucial for fully showcasing the potential of AR. 5G networks are considered a key force driving disruptive changes in AR technology due to their high speed, low latency, and high connectivity. The high bandwidth and low latency characteristics of 5G enable AR applications to transmit and process large amounts of data in real-time, providing users with a more immersive experience. In the grand narrative of digital transformation, augmented reality (AR) technology has attracted widespread attention due to its unique charm. Omerali and Kaya [13] provide a comprehensive framework to guide decision-makers in selecting the most suitable solution for their business needs among numerous augmented reality software. Through AR technology, ceramic enterprises can more intuitively display products, simulate operational processes, optimize workflow, etc., thereby improving work efficiency, reducing costs, and enhancing user experience. In the ceramic manufacturing industry, the application of AR technology is particularly widespread. AR technology can provide powerful support for the planning, execution, and validation of assembly and maintenance operations.

In the context of Industry 4.0, intelligent automation, including robots, is one of the current trends in the manufacturing industry. In Industry 4.0, network physical systems control the production of automated or semi-automated ceramic factories. However, this transformation is not always feasible and immediate, as certain ceramic technologies cannot provide the required flexibility. In this context, Pérez et al. [14] proposed a new method for process automation design, enhanced implementation, and real-time monitoring. The introduction of collaborative robots in the industry enables the combination of manual and automated production advantages. This method is based on creating a manufacturing process ceramic digital twin with an immersive virtual reality interface, which is used as a virtual test bench before physical implementation. Additive manufacturing (AM) and 3D printing technology have rapidly risen in the fields of materials science and industrial manufacturing due to their unique advantages. Among numerous methods for printing ceramics, direct extrusion has become a research hotspot in the field of 3D printing of ceramic materials due to its unique characteristics. The 3D printing method based on material extrusion is particularly eye-catching. It not only provides unprecedented innovation space for designers and engineers but also greatly promotes the manufacturing and application of ceramic materials [15]. Intelligent assembly is one of the key challenges currently faced by the manufacturing industry, especially in the pursuit of efficient, precise, and automated production environments. To address this issue, computer-aided intelligent assembly modelling methods based on design intent have emerged. This method aims to guide the assembly modelling process by capturing the designer's intentions during the design process, thereby reducing manual intervention and improving the level of intelligence. However, traditional computer-aided assembly modelling methods often rely on a large amount of manual intervention, with limited intelligence, which greatly limits the improvement of assembly efficiency and the reduction of costs. Shandong et al. [16] established a ceramic product information model for computer-aided intelligent assembly modelling DI capture based on the concept of interactive feature pairs developed in the early stage.

3D modelling plays a crucial role in the design and production of ceramic products, as it determines the appearance, structure, and final product quality of the product. In addition, the MAE comparative experiment further verified the advantages of the CNN algorithm in virtual scene information feature recognition, providing strong support for the classification, quality inspection, and design optimization of ceramic products. Wu and Song [17] focus on ceramic products, deeply integrating CAD technology, VR technology, and Convolutional Neural Networks (CNN) for 3D modelling and design optimization of ceramic products. CAD technology has greatly improved the efficiency and accuracy of ceramic product design with its precise size measurement and efficient modelling capabilities. In the ceramic design scenario, the 3D modelling method of ceramics based on CAD, VR, and CNN proposed in this article has achieved significant results. Yang et al. [18] analyzed ceramic materials used for tactile technology in virtual and augmented reality. In this process, remote adaptive technology has become a key force driving the innovation of VR/AR interactive experience with its unique advantages. Zhang et al. [19] used the Kano model analysis method to determine user needs and, based on this, studied the specific functional module content of the system. The necessity of researching virtual experiences in ceramic art has been determined through the current status of digital research on ceramic culture. A module partitioning method based on axiomatic theory is proposed for the modular creation experience of ceramic shape design. On the basis of determining the system functions, using Unity 3D engine combined with C # language, complete the writing of functional operation scripts to achieve interactive effects. Functional testing was conducted on the system, and a system testing process and evaluation table for system functional elements were designed. Based on user feedback data, the system's functional modules were summarized and analyzed, providing direction for system optimization. Selecting a teapot for instance analysis and design has achieved interactive modular creative experience in ceramic shape design. The paper constructs an interactive system design model based on ceramic art production and verifies the feasibility of modular design of ceramic shapes. Simultaneously, using 3D modelling software to construct a realistic casting scene model enhances the user's sense of realism and immersion. Not only can it break the limitations of traditional pottery in terms of venue, materials, technology, etc., and provide users with a good experience, but it can also promote the inheritance of ceramic culture.

3 THEORETICAL BASIS OF VR SYSTEM FOR CERAMIC DESIGN

3.1 Overview of VR Technology

VR technology utilizes computers to generate and enable experiences within virtual worlds. By replicating human senses like audio-visual and tactile perception, it immerses users into an ultra-realistic 3D virtual setting. In this simulated space, users can view the 3D virtual scenery via a helmet display and engage with virtual items using tools like data gloves. In the realm of ceramic design, VR technology offers designers a genuinely creative space, allowing them to craft based on authentic emotions. Additionally, it instantly visualizes the design's impact, giving designers a preview of the final product's appearance and texture during the creative process. VR technology facilitates more intuitive communication between designers and clients, thereby enhancing design efficiency and client contentment.

3.2 Multi-Modal Sensing Technology

Multi-modal perception technology refers to enhancing users' perception and understanding of the virtual environment by integrating multiple perception modes (such as vision, hearing, touch, etc.). Introducing multi-modal sensing technology into ceramic design VR system can improve the interactivity and intuition of design, as shown in Table 1:

Perceptual mode	*Functional description*	*Influence on ceramic design*
Visual mode	Provide rich visual information	Help designers accurately judge the key attributes of ceramic products such as shape, colour and texture.
Auditory mode	Provide operational feedback and ambient sound effects	Enhance the designer's immersion in the virtual environment through sound prompts and surround sound effects.
Tactile mode	Allow designers to feel virtual ceramics through touch	Designers can perceive the texture and weight of ceramics, making the design process more intuitive and real.

Table 1: The role of multi-modal sensing technology in ceramic design VR system.

By integrating these perceptual modes, designers can get more comprehensive and accurate design feedback, thus improving design efficiency.

3.3 The Application of CAD Technology in Ceramic Design

CAD technology is one of the important tools in the field of modern design. It uses computer technology to assist designers in the process of creating and modifying design schemes. The use of CAD in ceramic design can bring many advantages: CAD technology can accurately represent the shape and size information of ceramic products; CAD software provides rich editing functions such as stretching, rotating, and mirroring, which is convenient for designers to modify and improve the design scheme quickly. CAD technology can also be combined with VR technology to realize the seamless connection between design and simulation.

Combining CAD technology with VR has obvious advantages in ceramic design, as shown in Table 2:

Dominant dimension	*Detailed explanation of advantages*
Real-time modification and preview	Designers can directly operate the CAD model in the virtual environment, make real-time design modifications and preview the effect immediately.
Realistic rendering	VR technology provides high-quality rendering for CAD design, which makes

effect	the design effect more realistic and helps designers to accurately evaluate the visual effect of the design scheme.
Interactive experience enhancement	Designers can interact with CAD models in the virtual environment and feel the actual effect of the design scheme more intuitively so as to find potential problems in the design stage.
Improvement of design efficiency	Through real-time modification, preview, and realistic rendering effects, designers can iterate the design scheme faster, thus improving the design efficiency.
Design risk reduction	Designing and testing in a virtual environment can greatly reduce the problems in actual production and reduce the risk of design failure.
Product quality improvement	Through testing and optimization in VR, higher-quality ceramic products can be produced.
Customer satisfaction improvement	Because of the realistic preview of the design scheme and the optimized product design, customers can see the final effect earlier and more accurately, thus improving customer satisfaction.

Table 2: Advantages of combining CAD technology with VR in ceramic design.

This blend boosts design efficiency and significantly diminishes design risks, elevating product quality and customer contentment.

4 CERAMIC DESIGN VR SYSTEM DESIGN INTEGRATING MULTI-MODAL PERCEPTION AND CAD

The overall design of this system aims to build a comprehensive ceramic design platform integrating multi-modal perception, CAD technology, and VR. The overall architecture of the system includes several core functional modules in Table 3.

Functional module	*Functional module description*
User interface layer	Provide a friendly interface for users to interact with the system, including a design operation interface, perception feedback interface, and result display interface. Responsible for receiving the user's input instructions and displaying the system output results.
VR environment	Construct a highly realistic three-dimensional ceramic design environment in which users can design, modify and preview ceramic products; Support real-time rendering and dynamic interaction; and Provide an immersive design experience.
Multi-modal perception fusion module	Integrate information from different perceptual modes to provide users with all-around design feedback. Perceptual data is fused by algorithms to capture users' design intent and provide operational feedback.
CAD data processing module	Processing CAD model data, including model import, export, editing and modification; Closely integrated with VR system to realize seamless connection between design and simulation; Allows users to directly manipulate CAD models in a virtual environment.
Data storage and management module	Store and manage user's design data, perception data and system configuration information; Provide data retrieval, backup and recovery functions to ensure the safety and traceability of design data.
System control module	Comprehensive management and scheduling of the whole system to ensure the cooperative work among various functional modules; Handle system anomalies and errors, and provide user assistance and feedback mechanism.

Table 3: Overall framework of the comprehensive ceramic design platform.

The multi-modal sensing fusion algorithm is one of the key technologies to realize the core functions of this system. In order to build a VR system that can integrate different perceptual information such as vision, hearing and touch, an efficient multi-modal perceptual fusion algorithm has been specially designed for this paper. The design goal of this algorithm is to integrate information from different perceptual modes so as to improve the interactivity and intuition of design and provide designers with a more natural and smooth design experience. Data preprocessing is the first step to ensure the accuracy of multimodal perception fusion. Because the original data of different modes are different in format, sampling rate, and dynamic range, it is necessary to preprocess them to eliminate these differences. The preprocessing steps mainly include denoising and normalization. Denoising eliminates noise and outliers in the original data and improves data quality. Moving average is a common denoising method, which smoothes data points by calculating the average value of data within a certain window. Assuming that there is time series data $x_1, x_2, x_3, \dots, x_n$ and a window size w is selected, the moving average denoised data y_i can be calculated by the following formula:

$$y_i = \frac{1}{w} \sum_{j=i-w+1}^{i} x_j \tag{1}$$

Where i represents the index of the current data point.

Normalization is to map the data of different modes to the same scale, which is convenient for subsequent feature extraction and data fusion. Normalization is a common data preprocessing technology that aims to scale the features of data to a fixed range so that different features have similar numerical importance. The min-max normalization method zooms the data into the range of [0,1]. For each element x_{ij} in the feature matrix X, the normalization formula is:

$$x_{ij}^{'} = \frac{x_{ij} - \min_j x_{ij}}{\max_j x_{ij} - \min_j x_{ij}} \tag{2}$$

Where $x_{ij}^{'}$ is the normalized eigenvalue, $\min_j x_{ij}$ and $\max_j x_{ij}$ are the minimum and maximum values of the elements in the i row and the i column in the original eigenvalue matrix, respectively.

The Z-score normalization method standardizes the data to a normal distribution with a mean value of 0 and a standard deviation of 1. For each element $N_{new}\ x_{ij}$ in the feature matrix $N_{new}\ X$, the normalization formula is:

$$x_{ij}^{'} = \frac{x_{ij} - \mu_j}{\sigma_j} \tag{3}$$

Where μ_j is the mean of the j feature, and σ_j is the standard deviation of the j feature.

In the preprocessed data, it is necessary to extract the features that can represent the modal information. For visual mode, the algorithm pays attention to features such as shape, color, and texture, which are very important to describe the appearance of ceramic design. For auditory mode, the characteristics of sound, such as rhythm and tone, are mainly extracted to reflect the sound feedback in the process of ceramic design. For tactile mode, this paper focuses on tactile and pressure characteristics to simulate the real tactile feeling of ceramic materials.

Data fusion is the core of the multimodal perception fusion algorithm. The fusion level and pattern classification of the algorithm are shown in Figure 1.

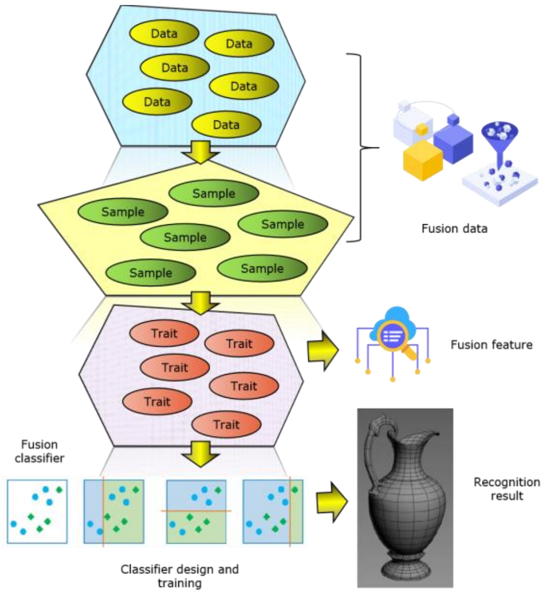

Figure 1: Fusion hierarchy and pattern classification.

In the step of data fusion, this paper uses weighted average and Kalman filter fusion algorithms to fuse the features of different modes effectively. The weighted average fusion algorithm fuses the features of each mode by assigning a weight and then calculating the weighted average. Suppose there are two modes A and B, their eigenvectors are a and b respectively, and their weights are w_A and w_B respectively, and:

$$w_A + w_B = 1 \tag{4}$$

The weighted average fused feature vector c can be calculated by the following formula:

$$c = w_A a + w_B b \tag{5}$$

Kalman filter is a recursive filter for linear dynamic systems, which can estimate the state of the system through prediction and updating steps. In multimodal data fusion, the Kalman filter can be used to fuse sensor data with different accuracy and different noise. Assuming that there are two modes A and B, their state estimations are $\hat{x}_A$ and $\hat{x}_B$ respectively, and the error covariance is P_A and P_B respectively, the state estimation $\hat{x}_F$ after Kalman filter fusion can be calculated by the following steps:

Prediction steps:

$$\hat{x}_F = \hat{x}_A \tag{6}$$

$$P_F = P_A \tag{7}$$

Update steps:

$$K = P_F H \left(H P_F H^T + R\right)^{-1} \tag{8}$$

$$\hat{x}_F = \hat{x}_F + K\left(z - H\hat{x}_F\right) \tag{9}$$

$$P_F = \left(1 - KH\right) P_F \tag{10}$$

Where z is the observation value, H is the observation matrix, and R is the covariance of the observation noise? K is the Kalman gain, which determines the influence of the observed values on the state estimation. An important feature of this algorithm is that it can dynamically adjust the weights according to the reliability of different modes, thus realizing adaptive fusion (as shown in Figure 2). In practical application, the Kalman filter can be adjusted and optimized according to the dynamic properties of the system.

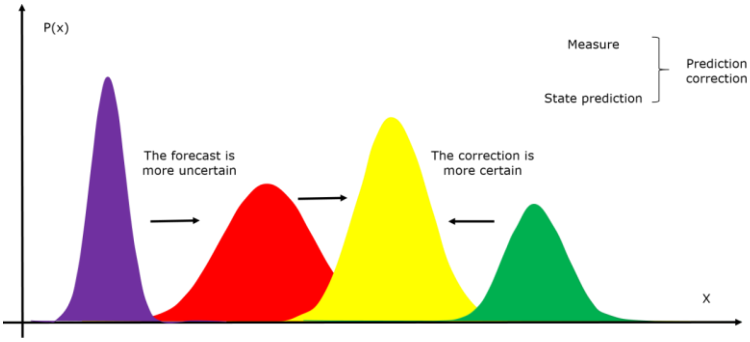

Figure 2: Kalman filtering.

This fusion method can comprehensively consider the information of each mode and generate a comprehensive perception result. The fusion result not only contains the complementary information of each mode but also reflects the attributes and states of the design object more comprehensively, thus improving the interactivity and intuition of the design. Based on the fusion results, decisions can be made and corresponding operational feedback and design suggestions can be provided for users. For example, in the process of ceramic design, when the designer adjusts the ceramic shape in the virtual environment, the multimodal perception fusion algorithm can judge the designer's intention in real-time and give appropriate modification suggestions according to the fusion results. These suggestions can help designers find satisfactory design schemes faster and improve design efficiency.

The integration of CAD and VR systems is the key link to realize the seamless connection between design and simulation. The specific implementation methods are as follows: (1) Data interaction mode: The general data exchange format is adopted to realize the import and export functions of CAD model data. At the same time, an API interface is provided to support customized data interaction to meet the needs of different CAD software. Analyze and render CAD model data in a VR system, and realize the visual display and operation interaction of the model in a virtual environment. (2) Presentation method of CAD model: In the VR environment, appropriate rendering technology and optimization algorithms are adopted to present the realism and detail level of the CAD model. The visual effects in the real world are simulated by adjusting the parameters such as illumination and materials. In addition, it also supports real-time editing and modification of CAD models so that designers can quickly iterate and optimize design schemes in a virtual environment. In order to enhance interactivity, the system also supports the operation of CAD models through gesture recognition, voice control, and other ways to improve design efficiency.

5 REALIZATION AND SIMULATION EXPERIMENT OF VR SYSTEM FOR CERAMIC DESIGN

5.1 System Implementation

In the process of system implementation, this paper chooses the appropriate development environment and tools and elaborates on the details of the implementation of key technologies. This system was mainly developed with the support of a Unity3D engine and C# programming language.

Unity3D is a widely used game and VR application development platform, which provides rich graphics rendering, physical simulation and user interaction functions. As the main programming language of Unity3D, C# has powerful object-oriented features and easy-to-understand syntax, which makes the system development more efficient and stable.

Construction of VR environment: This paper uses the terrain system and architectural system of Unity3D to create a realistic ceramic design studio environment. By finely adjusting the visual effects such as lighting, materials and shadows, the virtual environment is more realistic.

Multi-modal perception fusion: In order to realize multi-modal perception fusion, this paper integrates visual, auditory and tactile feedback mechanisms. Visual feedback is achieved through high-quality rendering of Unity3D, auditory feedback uses spatial audio technology to simulate the sound propagation in a real environment, and tactile feedback simulates the touch of ceramic materials through force feedback equipment.

Integration of CAD data: This paper realizes seamless integration of CAD data and VR systems by importing CAD models into Unity3D. Designers can directly operate these CAD models in the virtual environment and make real-time design modifications and previews.

5.2 Simulation Experiment Design and Result Analysis

To validate the system's excellent performance, various simulation experiments are devised in this segment. The primary objective of these experiments is to assess the system's interactivity, intuitiveness, and efficiency specifically during the ceramic design process. Therefore, the following experimental scheme is designed:

User experience test: Invite designers from different backgrounds to use this system, and record their feedback and experience in the design process, as shown in Table 4 and Figure 3.

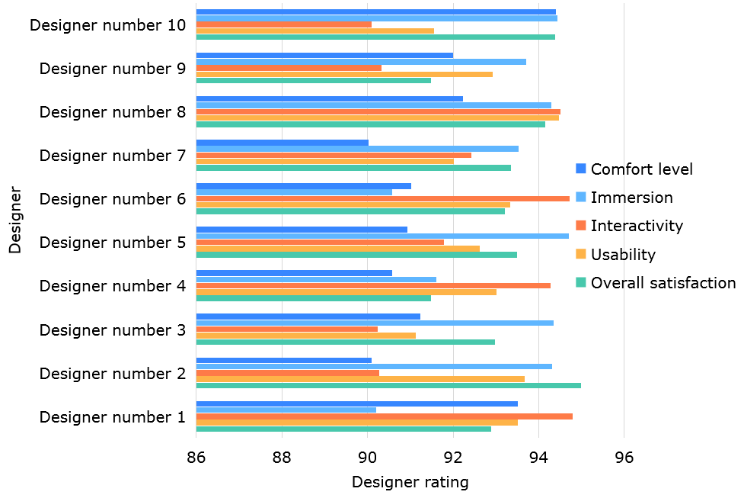

Figure 3: User experience rating results.

Evaluation dimension	*Opinions from consumers*
Overall satisfaction	
Positive opinion	"The overall function of the system is perfect, which meets the needs of ceramic design well."
	"After use, I feel that the ceramic design becomes simpler and more intuitive."
Negative	"Occasionally there will be a stuck phenomenon, and I hope the system will be

opinion	smoother."
Usability	
Positive opinion	"The interface layout is reasonable, and novices can get started quickly."
	"The operation logic is clear and the steps are easy to understand."
Negative opinion	"Some functions are hidden deeply and need to be clicked many times to find them."
Interactivity	
Positive opinion	"The system responds quickly and the instructions are conveyed accurately."
	"Multi-modal perception fusion makes the design process more natural."
Negative opinion	"In some cases, the feedback from the system is not timely enough."
Immersion	
Positive opinion	"The VR environment is realistic, making people feel like they are in a ceramic workshop." "The combination of sound and visual effects enhances the immersive experience."
Negative opinion	"Occasionally, there will be a delay in the picture, which will affect the immersion."
Comfort level	
Positive opinion	"After using the system for a long time, there is no obvious discomfort in the eyes and body."
	"The user interface is friendly and ergonomic."
Negative opinion	"Some users report that the helmet is slightly heavier and will feel tired after wearing it for a long time."

Table 4: User experience feedback detailed opinion table.

Comparison of design tasks: Let designers complete the same design tasks in the design environment without multimodal perception and in this system, respectively (see Figure 4 for some examples), and compare the design time and quality of the two systems.

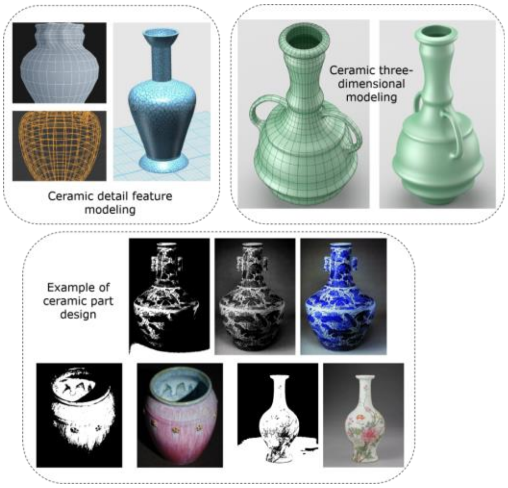

Figure 4: Some examples of designer's design tasks.

Figure 5 shows the design time comparison between them, and Figure 6 shows the design quality comparison between them.

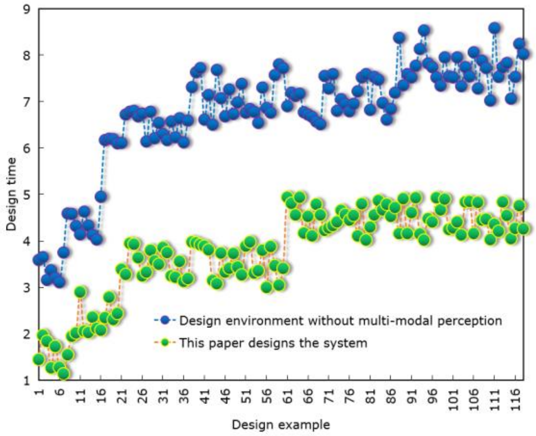

Figure 5: Comparison of design time.

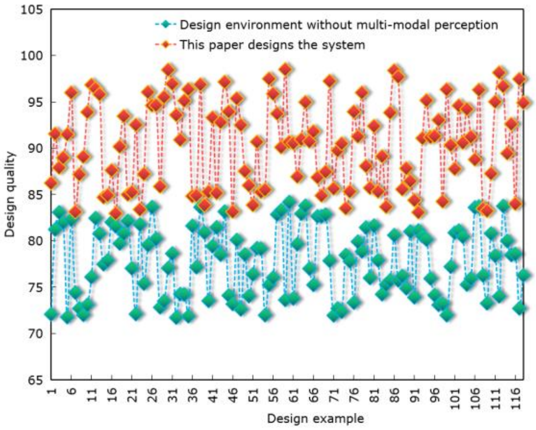

Figure 6: Comparison of design quality.

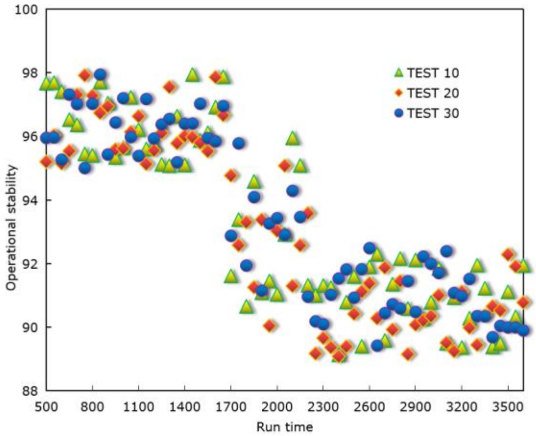

Figure 7: Operation stability of the system.

System performance test: Test the running stability and response speed of the system under different configurations. The operation stability of the system is shown in Figure 7. The response speed of the system is shown in Figure 8.

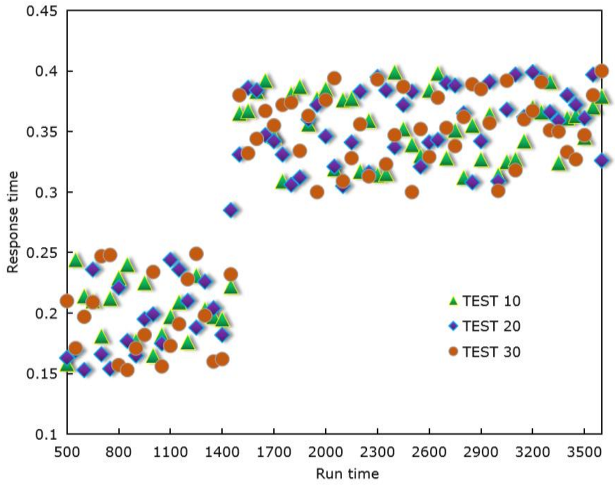

Figure 8: The response speed of the system.

Through the above experiments, a large number of data have been collected, and the experimental results are analyzed in depth as follows:

User experience: Most users said that the system provided a more intuitive and immersive design experience, making the design process more interesting and efficient.

Design efficiency: Compared with the design environment without multi-modal perception, designers who use this system have shortened the completion time of design tasks by 65% on average, and the innovation and practicability of design results have also been significantly improved.

System performance: Under different configurations, the system has good running stability and response speed, which meets the requirements of real-time interaction and design preview.

Combined with the above experimental results, this system significantly improves the interactivity and intuition of ceramic design by integrating multi-modal sensing and CAD technology. The experimental results demonstrate the effectiveness of the system in enhancing design efficiency, refining user experience, and maintaining robust system performance. Looking ahead, we plan to refine the system's functionalities and user experience even further, thereby fostering innovative growth within the ceramic design industry.

6 CONCLUSIONS

This article not only successfully implements a ceramic design VR system that integrates multimodal perception and CAD technology but also proves its significant value in practical applications. Through VR technology, designers can create directly in a 3D environment without the need to frequently switch between 2D drawings and 3D models, significantly improving design efficiency. This system not only provides new design tools and methodologies for the ceramic design industry. This system combines the immersive experience of VR technology with the precision of CAD technology, opening up a new design dimension for ceramic designers. In order to achieve more realistic simulation effects, it conducts more in-depth research on the physical properties of ceramic materials and achieves more precise simulation in virtual environments. The immersive VR experience allows designers to fully immerse themselves in design, enjoy the fun of creation, and provide a more intuitive and convenient way for design review and communication. The VR system provides designers with a virtual environment that is almost identical to the real world, making the design process more intuitive and helping designers better understand and evaluate the feasibility and effectiveness of design solutions.

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