ARO-CapsNet: A Novel Method for Evaluating User Experience in Immersive VR Furniture Design

Yin Luo, Jun Liu*, Li Zhang
College of Fine Arts and Design, WenZhou University, WenZhou 325035, ZheJiang, China

Abstract*—Immersive virtual reality (VR) technology has become an essential tool in enhancing user experience across industries, particularly in furniture design. With the ability to provide realistic, interactive, and immersive environments, it significantly improves user engagement and decision-making in product design. However, existing analysis methods lack precision in evaluating user experience within VR environments. This study aims to develop a more accurate and efficient model for analyzing the application of immersive VR in future furniture design. By integrating the Artificial Rabbit Optimization (ARO) algorithm with Capsule Networks (CapsNet), this research enhances the evaluation of user experience in immersive VR environments. The proposed method uses the ARO algorithm to optimize the parameters of CapsNet, which maps the relationship between the analysis indicators of furniture design and user experience. This model is tested against traditional methods such as CNN and CapsNet alone. The analysis focuses on key factors such as visual elements, interaction, and system performance, with performance metrics like root mean square error (RMSE) and R^2 value used for evaluation. Experimental results show that the ARO-CapsNet model achieves a RMSE of 0.17 and an R^2 value of 0.988, outperforming both CNN and CapsNet in terms of accuracy and efficiency. Additionally, the proposed model improves the immersive VR system's ability to deliver accurate user experience evaluations, making it a superior method for analyzing future furniture design applications. The integration of the ARO algorithm with CapsNet significantly enhances the precision of immersive VR user experience evaluations in furniture design. The ARO-CapsNet model not only improves evaluation accuracy but also increases system efficiency, providing a robust framework for future applications of VR in product design.

Keywords*—*Immersive virtual reality; furniture design; application analysis; artificial rabbit optimisation algorithm

I. INTRODUCTION

Due to advancements in science and technology, the production of furniture has consistently risen, leading to heightened rivalry among furniture companies. Additionally, consumer attitudes towards consumption have shifted, resulting in increasingly high expectations for user experience [1]. The technology used for furniture presentation has inherent biases and constraints, resulting in a passive role for the buyer and directly impacting the consumer experience [2]. With the progressive advancement and enhancement of virtual reality technology in recent years, significant achievements have been made. Its interactive capabilities have greatly enhanced the user experience and expanded the scope of research in the domestic furniture virtual display field. This has a significant impact on the development direction of furniture enterprises [3]. Virtual display technology utilizes computer technology to create three-dimensional models of furniture products, which can be accessed and interacted with by users through computers or networks. This technology enables users to have a realistic sensory and emotional experience with furniture products.

The integration of advanced virtual reality technology in furniture design and user experience research enables users to fully immerse themselves in virtual displays, enhancing the depth of information, realism, and overall user experience [4]. This has significant practical applications. At now, immersive virtual reality technology is being used to study several areas of future furniture design, user experience, and application analysis [5]. Svalina et al. [6] examined the use of immersive virtual reality technology to create a virtual exhibition hall. Jafarifiroozabadi et al. [7] developed a virtual reality technology specifically for train driving simulations, which includes realistic acoustic sounds to enhance the user's auditory immersion. Zhang et al. [8] combined virtual reality technology with furniture display design to create a furniture virtual display system that offers users an intuitive and realistic interactive experience. Potseluyko et al. [9] used the LSSVM model to construct an application analysis system for virtual reality technology in future furniture design, using the case of ancient towns in Sichuan and Chongqing for performance analysis. Lastly, Ji et al. [10] proposed a user experience analysis method for future furniture virtual display, utilizing an intelligent optimization algorithm to improve the neural network model. Based on extensive literature study and survey analysis, it can be stated that immersive virtual reality technology and furniture design analysis application has the following features [3]: a. The study on the future furniture virtual display system solely focuses on qualitative analysis and lacks quantitative analysis. The current furniture virtual display system lacks a comprehensive examination of the user experience and performance metrics. Current machine learning algorithms that analyze the use of virtual reality technologies lack adequate accuracy in their evaluation models. The use of intelligent optimization algorithms has led to the creation of a model optimization approach for analyzing the application of virtual reality technology. This approach aims to enhance the accuracy of virtual reality technology analysis [11].

This study presents a way for analyzing and using immersive virtual reality technology in furniture design. The approach is based on intelligent optimization algorithms and deep learning algorithms. The method examines the challenges of using virtual reality in furniture design from a user experience perspective. It identifies key analysis factors and utilizes the efficient optimization capabilities of the artificial rabbit optimization algorithm [12] to optimize the parameters of the capsule network

*Corresponding Author.

model [13]. Additionally, it constructs a design application analysis algorithm based on the ARO-CapsNet model. Through comparative analysis validation, the proposed method in this paper demonstrates superior performance.

II. Immersive Virtual Reality in Furniture Design-User Experience

A. *Immersive Virtual Reality in Furniture Design-User Experience Application Issues in Analysis*

1) Immersive virtual reality: Immersive Virtual Reality (Immersive VR) technology [14] refers to the utilization of three-dimensional input and output devices and software systems to create virtual simulation environments on computers. These environments are designed to be interactive and immersive, providing the user with a multi-channel sensory experience that gives the illusion of being in a virtual environment, as depicted in Fig. 1.

An immersive VR system usually consists of three parts: a reality system, a processing control system, and a motion capture system [15], and its composition is shown in Fig. 2.

Immersive virtual reality technology as a virtual reality technology in the more advanced, more complex a comprehensive technology, its system and table and virtual reality system, AR system and distributed virtual reality system, compared with the following characteristics [15]: 1) immersive; 2) follow the movement; 3) real-time, specific as Fig. 3.

Fig. 1. Effect of immersive virtual reality technology.

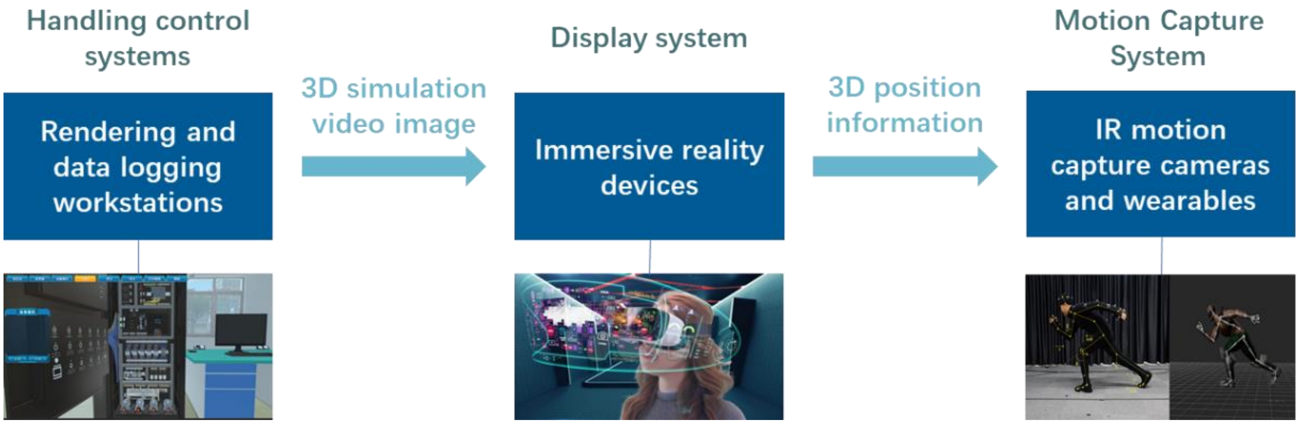

Fig. 2. Immersive virtual reality system composition.

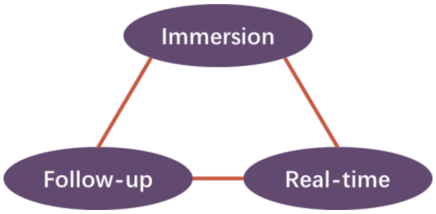

Fig. 3. Characteristics of immersive virtual reality technology.

2) Immersive VR technology in furniture design-user experience: The use of immersive virtual reality (VR) technology in furniture design and user experience is progressively intensifying. This enables consumers to have a comprehensive experience prior to making a purchase by offering an immersive environment, as seen in Fig. 4. The applications of immersive virtual reality (VR) technology in furniture design-user experience encompass various features such as virtual reality roaming, real-time design interaction, home atmosphere simulation, customized experience, cost and resource saving, panoramic home display, integration of virtual and reality, optimization of user experience, remote observation, and multimedia embedding [16].

Fig. 4. Analysis of immersive virtual reality technology applications.

B. Extraction and Construction of Indicators for Applied Analysis

1) Immersive VR technology application process: The steps of immersive VR technology application in furniture design-user experience are shown in Fig. 5, and the specific steps include 3D furniture scene design, scene furniture modelling, adjusting lighting, scene roaming, adding detail display, furniture attribute replacement, and system release, etc. [17].

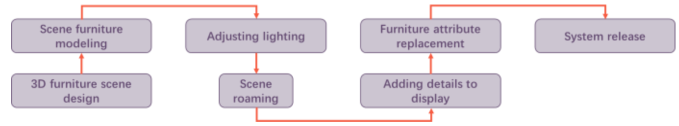

Fig. 5. Steps in the application of immersive virtual reality technology.

2) Application analysis indicator extraction: According to the analysis of the application of immersive VR technology in furniture design-user experience, this paper analyses the visual elements, psychological elements, creating space, colour design, etc., and the construction of the specific indicator set is shown in Fig. 6.

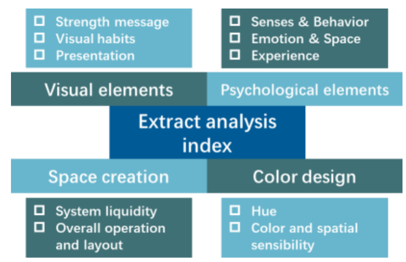

Fig. 6. Extraction and construction of indicators for analysing the application of immersive virtual reality technology.

C. Application Analysis Programme Design

This paper proposes a method for analyzing the application of immersive VR technology in furniture design, specifically focusing on user experience issues. The method is based on intelligent optimization algorithms and deep learning. The detailed design scheme is illustrated in Fig. 7. The immersive VR technology application analysis research technique encompasses several essential technologies, including VR application analysis, application analysis scheme design, application analysis model construction and optimization, and case design analysis.

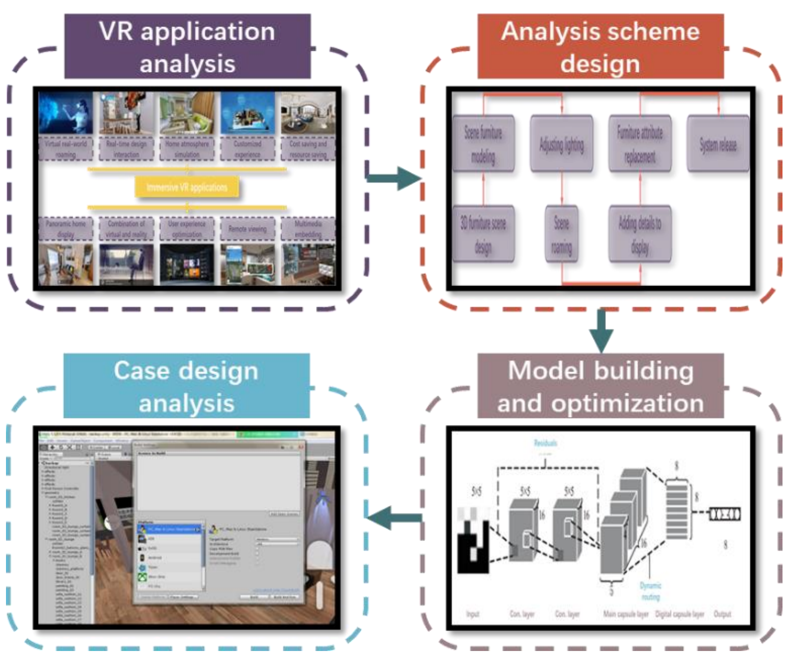

Fig. 7. Immersive virtual reality technology application analysis programme.

III. Application of Virtual Reality Furniture Design

A. ARO Algorithm

Artificial rabbits optimization (ARO) [18] is a nature-inspired swarm intelligence optimisation algorithm. The ARO algorithm is inspired by the survival strategies of rabbits in nature (Fig. 8), including meandering foraging and random hiding. The meandering foraging strategy forces a rabbit to eat grass near other rabbits' nests, which prevents its nest from being discovered by predators. The random hiding strategy allows the rabbit to choose a random burrow among its own to hide in, which reduces the likelihood of being captured by an enemy. In addition, the rabbit's energy contraction causes it to shift from a meandering foraging strategy to a random hiding strategy. The algorithm mathematically models this survival strategy to develop a new optimiser.

Fig. 8. ARO algorithm inspired behaviour.

In the phase of initialising the artificial rabbit population, a certain number of individual rabbits are randomly generated in the space of the defining domain, and each rabbit represents a possible solution in the problem space. And then, the function values of these individuals are calculated based on their locations.

1) Bypass foraging (exploration): When foraging, rabbits will search far away and ignore what is close by. They only eat grass from other areas and not from their own area, a foraging behaviour known as meandering foraging.ARO's meandering foraging behaviour suggests that each searching individual tends to update its position to another randomly selected searching individual in the group with an added perturbation. The specific model is as follows:

$$X_i(t+1) = X_j(t) + R\cdot\left(X_i(t) - X_j(t)\right) + round\left(0.5\cdot(0.05+r_1)\right)\cdot r_2 \tag{1}$$

$$R = L\cdot c \tag{2}$$

$$L = \left(e - e^{\left(\frac{t-1}{T}\right)^2}\right)\cdot \sin\left(2\pi r_3\right) \tag{3}$$

$$c(k) = \begin{cases} 1 & if\ k == g(l) \\ 0 & else \end{cases} \quad k = 1,\cdots,d\ and\ l = 1,\cdots,\lceil r_3\cdot d\rceil \tag{4}$$

$$g = randperm(d) \tag{5}$$

$$n_1 \sim N(0,1) \tag{6}$$

Where $X_i(t+1)$ denotes the position of the ith rabbit; R denotes the moving step; T is the maximum number of iterations; $\lceil\cdot\rceil$ denotes the ceil function; $randperm$ denotes a random integer from 1 to d; r_1 , r_2 and r_3 are random numbers; n_1 denotes that it obeys a normal distribution. Fig. 9 gives the curve of the step size L with the number of iterations.

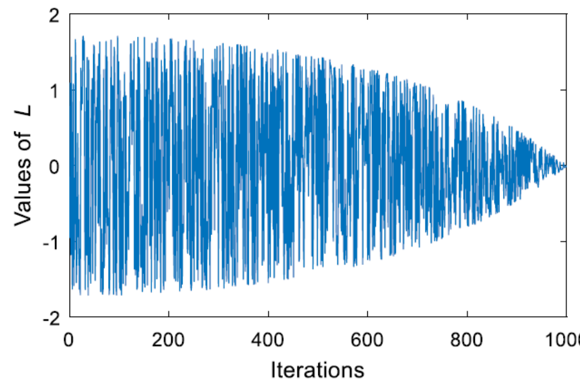

Fig. 9. Curve of step size with number of iterations.

2) Random concealment (exploitation): In order to hide from predators, rabbits usually dig a number of different burrows around their nests. In each iteration of the ARO algorithm, the rabbit always generates a number of burrows around it along each dimension of the search space, and always chooses one randomly from all the burrows to hide, in order to reduce the probability of being predated. The specific model is as follows:

$$X_i(t+1) = X_j(t) + H\cdot g\cdot X_i(t) \tag{7}$$

$$H = \frac{T-t+1}{T}\cdot r_4 \tag{8}$$

$$n_2 \sim N(0,1) \tag{9}$$

$$g(k) = \begin{cases} 1 & if\ k == j \\ 0 & else \end{cases} \quad k = 1,\cdots,d \tag{10}$$

In order to determine the next behaviour of the rabbit group, its energy factor needs to be calculated, which in turn determines the next behaviour of the individual, i.e. the choice of meandering foraging or random hiding. For the rabbit population, its energy factor at the tth iteration is calculated as shown in Eq. (11):

$$A(t) = 4\left(1 - \frac{t}{T}\right)\ln\frac{1}{r} \tag{11}$$

where r is a random number. Fig. 10 gives the curve of the energy factor A with the number of iterations, and Fig. 11 gives the schematic diagram of the search mechanism of the energy factor. Fig. 12 gives a schematic diagram of the calculation of the probability of bypass foraging.

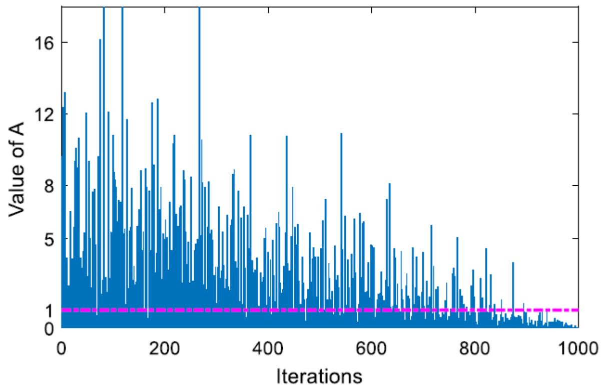

Fig. 10. Curve of energy factor A with number of iterations.

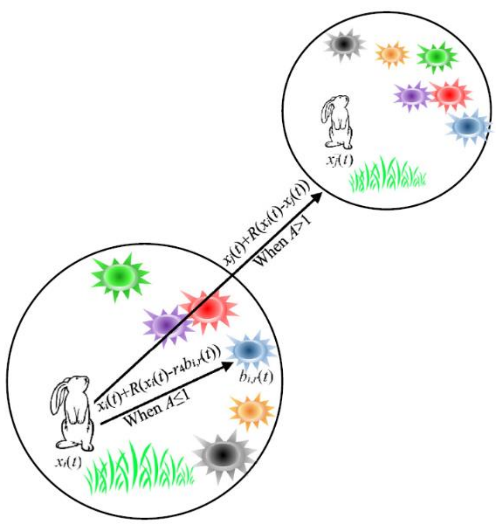

Fig. 11. The curve of step length with a number of iterations.

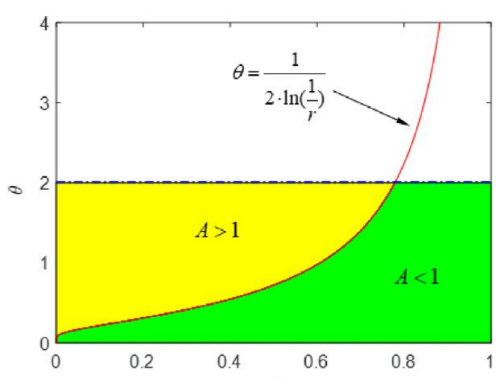

Fig. 12. Calculating the probability of foraging bypasses.

3) ARO process steps: According to the optimization behaviour of the ARO algorithm, the ARO flowchart is shown in Fig. 13, with the following steps: a. set the parameters of the ARO algorithm, including the number of populations, the maximum number of iterations, and other parameters; b. randomly initialize rabbit populations and evaluate the population position to obtain the optimal rabbit position; c. calculate the energy factor A; d. if A<1, update the populations by using a detour foraging strategy, or else use a random hiding strategy to update the population; e. Calculate the updated population position and obtain the optimal rabbit position; f. Determine whether the number of iterations reaches the maximum and output the final optimal solution.

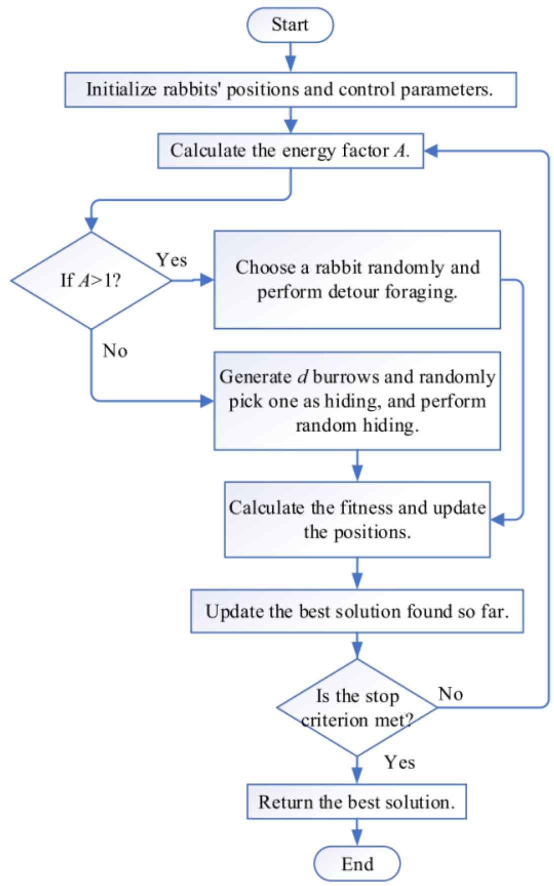

Fig. 13. Flowchart of ARO algorithm.

B. Capsule Network Model

Capsule Networks (CNNs) [19] are a novel deep learning model designed to overcome some of the limitations of traditional Convolutional Neural Networks (CNNs) [20] in processing images, especially in recognising the pose and spatial layout of objects. The core idea of capsule networks is to use so-called "capsules" instead of traditional neurons (as shown in Fig. 14), which are a collection of neurons that collectively represent the instantiated parameters of an object, such as position, size, and orientation. The capsule network learns the relationships between different capsules through a dynamic routing algorithm that allows the network to adaptively focus on relevant features and suppress irrelevant information.

The residual block structure is introduced in the capsule network [21], in order to reduce the number of parameters in the model and improve the robustness of the model. The improved capsule network structure is shown in Fig. 15.

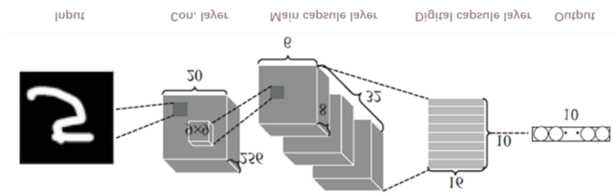

Fig. 14. CapsNet network structure.

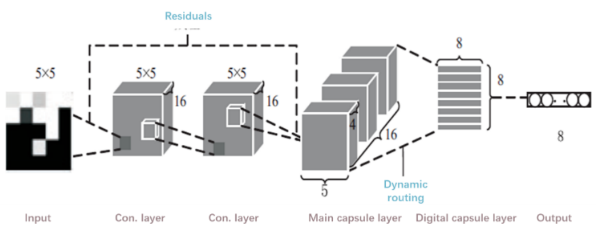

Fig. 15. Improved CapsNet network structure.

The core of a capsule network is a capsule, which is a collection of neurons that together represent a feature vector in the input data, which has the advantage over CNN in that it can better deal with spatial relationships in the data. The core idea of dynamic routing algorithm in capsule network is to adjust the routing weights from the low-level capsule to the high-level capsule through iteration, so that the output vector of the low-level capsule can focus on the high-level capsule associated with it. The iterative process of dynamic routing algorithm in capsule network is described as follows:

$$c_{ij} = \frac{\exp(b_{ij})}{\sum_i \exp(b_{ij})} \tag{12}$$

$$u_{j|i} = W_{i|j} \times u_i \tag{13}$$

$$s_j = \sum_j c_{ij} \times u_{j|i} \tag{14}$$

$$v_j = \frac{\|s_j\|^2}{1+\|s_j\|^2} \times \frac{s_j}{\|s_j\|} = squash(s_j) \tag{15}$$

$$b_{ij} \leftarrow b_{ij} + u_{j|i} v_j \tag{16}$$

where b_{ij} denotes the prior probability that capsule i is connected to capsule j; $W_{i|j}$ is the transformation matrix; u_i is the output vector of low-level capsule i; $u_{j|i}$ is the predicted capsule; s_j is the total input of high-level capsules; and v_j is the output vector of high-level capsule *j*.

C. ARO-CapsNet Model Application Methodology

1) ARO-CapsNet model: In order to improve the analysis accuracy and design efficiency of the application of immersive VR technology in future furniture design and user experience, this paper adopts the CapsNet model to construct the application analysis model, and at the same time adopts the ARO algorithm to optimise the application analysis model. The ARO-CapsNet model takes the CapsNet network structural parameters as the optimisation variables, and takes RMSE as the fitness value function value, and adopts the ARO algorithm optimisation strategy to optimally find the CapsNet network structure parameters, as shown in Fig.16.

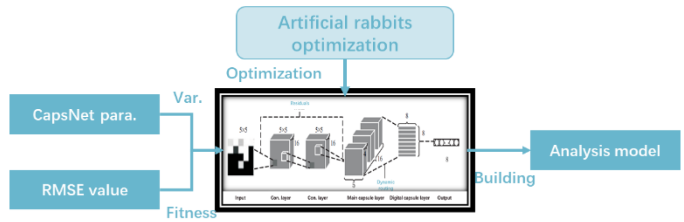

Fig. 16. ARO-CapsNet network model.

2) ARO-CapsNet application process: Based on the ARO-CapsNet model immersive VR technology in the future furniture design and user experience application analysis method by analysing the immersive virtual reality in furniture design-user experience application problems, extracting the application analysis indexes, constructing the index system, using the ARO-CapsNet model to construct the mapping relationship between the application analysis indexes and the assessment value, and obtaining the future furniture design and user experience application analysis model, the specific flow chart is shown in Fig.17.

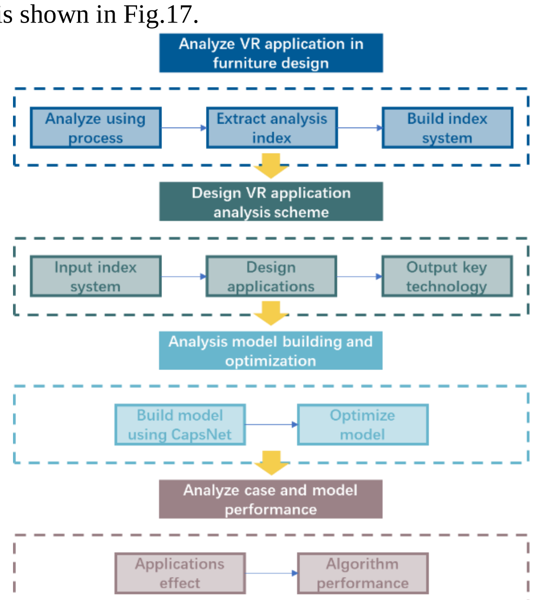

Fig. 17. ARO-CapsNet network model application process.

IV. Experiments and Analysis of Results

A. Experimental Set-up

For the future furniture design problem, this paper adopts Unity3D, 3Dmax and CAD software to develop and design [22], the specific development process is shown in Fig. 18.

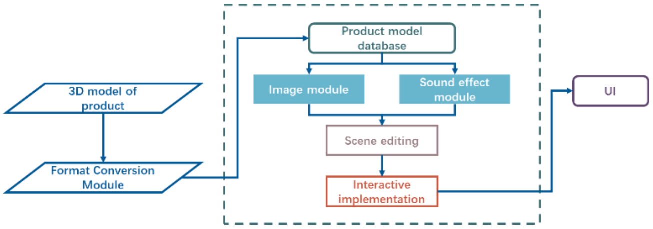

Fig. 18. System development process.

For the immersive VR technology application analysis problem, this paper uses CNN [23], CapsNet [19], ARO-CapsNet model for comparative analysis. The parameters of ARO algorithm are set as follows: the number of populations is 100, and the number of iterations is 1,000; the CNN network is set as follows: the convolutional layer is 100 nodes.

B. Analysis of Results

In order to analyse the application of immersive VR technology in future furniture design, this paper analyses the effect from three aspects: 3D modelling, interaction design and system release [24]. The effect diagram of the showroom is shown in Fig. 19. In Fig. 20, we add the design effect after adding relevant interaction elements. At the same time, the virtual system released on PC, IOS system and Android system is embedded in Fig. 21 to show the effect.

Fig. 19. 3D modelling effect.

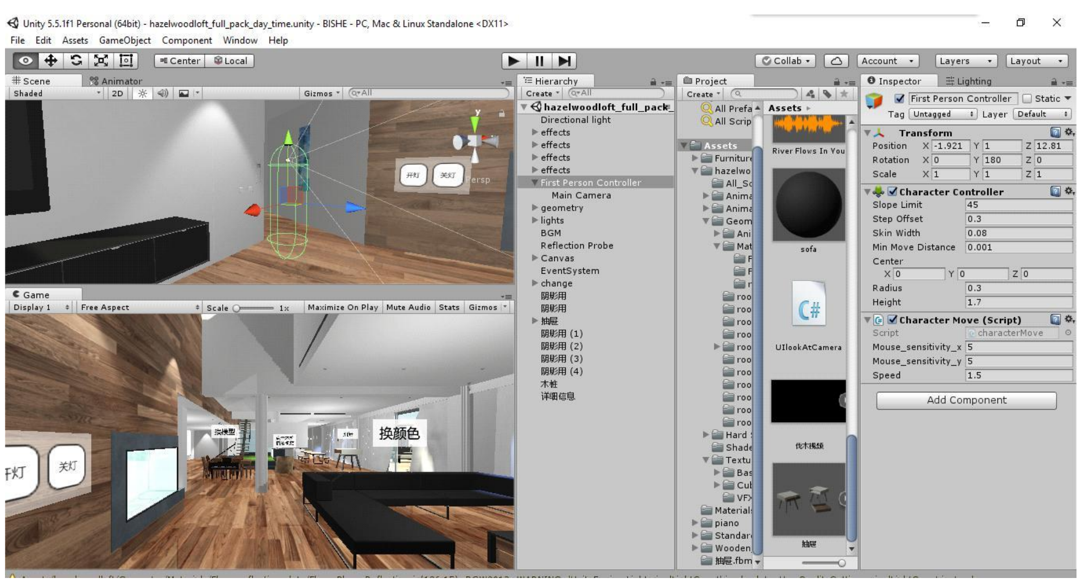

Fig. 20. Interaction design diagram.

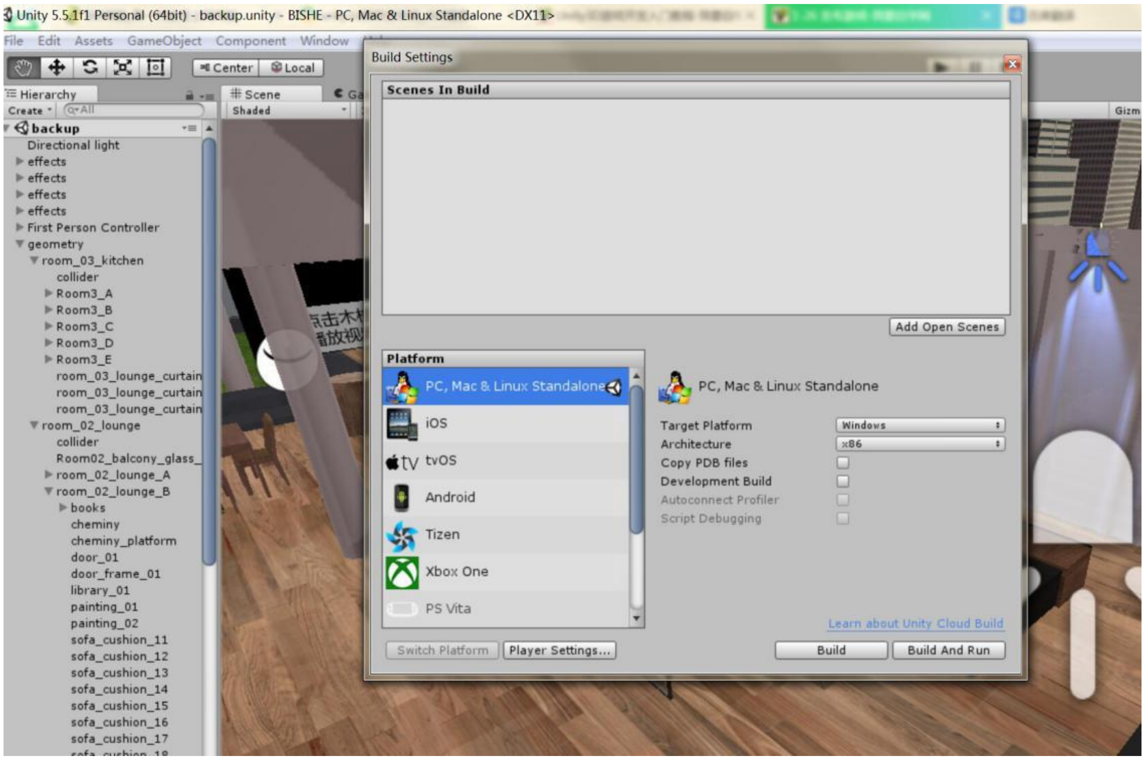

Fig. 21. Schematic system development.

To confirm the efficiency and superiority of the immersive VR future furniture design experience application analysis approach based on the ARO-CapsNet model, we compared and analyzed ARO-CapsNet with CNN and CapsNet. The findings are shown in Fig. 22 and Fig. 23.

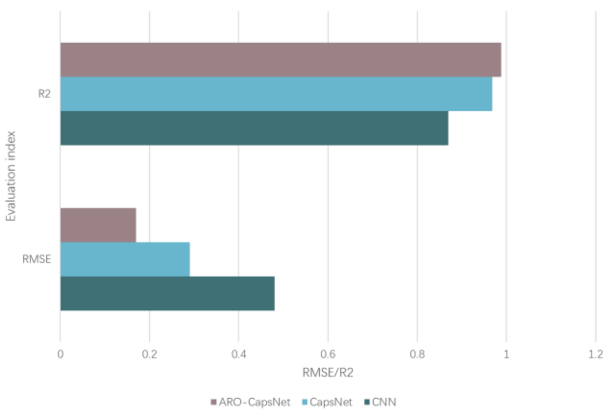

Fig. 22. Comparative analysis of application analytics model performance.

The performance of the application analysis models, namely ARO-CapsNet, CNN, and CapsNet, may be seen in Fig. 22 located in the center of our document. According to the figure. Based on the RMSE and R2 values, it is evident that the ARO-CapsNet model outperforms the other models in predicting application analysis. The RMSE for ARO-CapsNet is 0.17, which is the smallest among all models. Additionally, the R2 value for ARO-CapsNet is 0.988, indicating the highest level of accuracy compared to the other models. Figure The table displays the outcomes of the application analysis for each model in the comparison. Fig. 23 demonstrates that the application analysis technique of immersive VR future furniture design experience, which is based on the ARO-CapsNet model, accurately analyzes the value, bringing it closer to the actual value.

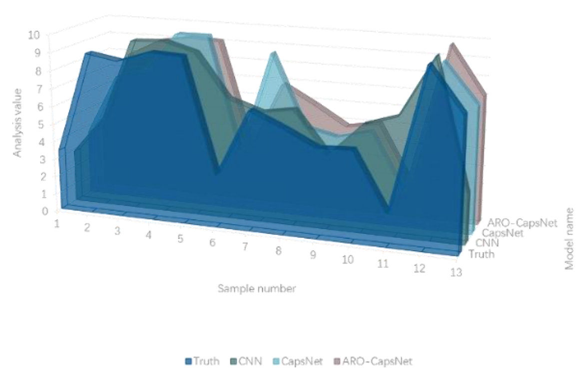

Fig. 23. Application analysis results of each algorithm.

V. CONCLUSION

To address the issues of poor accuracy and low design efficiency in the study of immersive VR technology applications, a novel technique is given. This method utilizes ARO and CapsNet to develop an immersive VR future furniture design experience application analysis method. The technique examines the indications of immersive VR technology application and formulates an application analysis scheme by analyzing the challenges faced in applying immersive virtual reality to furniture design from a user experience perspective.

The ARO algorithm is used to optimize the parameters of CapsNet in the analysis model for immersive VR technology application. Additionally, a new analysis model is developed for the future furniture design experience application in immersive VR, which is based on ARO-CapsNet. By doing experimental analysis and comparing it with other models, the suggested model demonstrates superior performance in application analysis. This further confirms that the model has more flexibility for future furniture design experiences.

References

[1] Grand A , Dittrich R , Francis B , Hinde J. Modelling changes over time in a multivariate paired comparison: An application to window display design:[J].Statistical Modelling, 2022, 22(1-2):95-106.

[2] Chung S E , Ryoo H Y .User Experience Factors and attributes on the Stretchable Display applied Automotive[J].International Journal of Asia Digital Art and Design Association, 2022, 26(1):1-11.

[3] Azadmanjir Z , Sadeghi-Naini M , Dashtkoohi M , Moradi-Lakeh M, Arabkheradmand J, Harrop J S. The design of a quality improvement dashboard for monitoring spinal cord and column injuries[J].Informatics in Medicine Unlocked, 2024, 47.

[4] Zhang J .User Experience Perspectives on the Application of Interactivity Design Based on Sensor Networks in Digital Museum Product Display[J].Journal of Sensors, 2022.

[5] Ortiz-Toquero S , Sanchez I , Serrano A , Martin R.Prevalence of Computer Vision Syndrome and Its Risk Factors in a Spanish University Population[J].Eye & Contact Lens: Science & Clinical Practice, 2024, 50(8):333-341.

[6] Svalina A , Pibernik J , Dolic J M L .Assessing the Design of Interactive Radial Data Visualizations for Mobile Devices[J].journal of imaging, 2023, 9(5).

[7] Jafarifiroozabadi R , Joshi R , Joseph A , Wingler D.Perceived Usability of Seating in an Outpatient Waiting Area: A Combined Approach Utilizing Virtual Reality and Actual Seating Prototypes:[J].HERD: Health Environments Research & Design Journal, 2022, 15(2):248-261.

[8] Zhang Y , Wang J , Ahmad R , Li X. Integrating lean production strategies, virtual reality technique and building information modeling method for mass customization in cabinet manufacturing[J].Engineering construction & architectural management, 2022.

[9] Potseluyko L , Rahimian F P , Dawood N , Elghaish F, Hajirasouli A. Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector[J].Automation in construction, 2022.

[10] Ji G , Sawyer A O , Narasimhan S G .Virtual home staging and relighting from a single panorama under natural illumination[J].Machine Vision and Applications, 2024, 35(4).

[11] Gong C., Xiang W., Chen Y. Optimization of process parameters for injection moulding products based on machine learning and genetic algorithms [J]. Machinery Manufacturing, 2024, 62(05): 60-65.

[12] Luo Jianfu. Adaptive diversity golden sine search improved artificial rabbit optimization algorithm [J]. Journal of Hulunbeier College, 2024, 32(03): 91-99.

[13] Zhang Huimin, Xie Zeqi. A method for identifying rice pests based on multi-scale hollow capsule twin networks [J]. Jiangsu Agricultural Sciences, 2024, 52(11): 231-237.

[14] Mazza T .Unity virtual reality development with VRTK4: a no-coding approach to developing immersive VR experiences, games, & apps[J].Computing reviews, 2023.

[15] Kablitz D , Conrad M , Schumann S .Immersive VR-based instruction in vocational schools: effects on domain-specific knowledge and wellbeing of retail trainees[J].Empirical Research in Vocational Education and Training, 2023, 15(1).

[16] Modoni G E , Sacco M .A Human Digital-Twin-Based Framework Driving Human Centricity towards Industry 5.0[J].sensors, 2023, 23(13).

[17] Li B , Zhou M , Bai Y .The relationships and trends of interregional virtual water trade based on an MRIO model[J].Water science & technology: Water supply, 2022, 22(3):2395-2406.

[18] Lam M C , Nizam S S M , Arshad H , Suwadi N A.Tangible interaction technique with authoring capability for kitchen design[J].Multimedia Tools and Applications, 2023, 82(19):30125-30150.

[19] Li Qi, Liu Chunxia, Gao Gaimei. Industrial Internet intrusion detection method based on CapsNet and SRU [J]. Computer Technology and Development, 2024, 34(07):93-99.

[20] Hashmi H , Dwivedi R K , Kumar A .Comparative Analysis of CNN-Based Smart Pre-Trained Models for Object Detection on Dota[J].Journal of Automation, Mobile Robotics and Intelligent Systems, 2024, 18(2):31-45.

[21] Zhang Hongying, Tian Penghua. A gait recognition method combining residual networks and multi-level block structures [J]. Journal of Electronic Measurement and Instruments, 2022(6):66-72.

[22] Yu Jin, Yan Shuguang, Lv Tong. Design and implementation of a virtual magnetic separation laboratory system based on Unity3D [J]. Software Engineering and Application, 2024, 13(3):8.

[23] Lin Wei, Chen Yan. Chinese microblog sentiment analysis based on BERT-BiGRU and multi-scale CNN [J]. Journal of China Electronics Technology Group Corporation, 2023, 18(10):939-945.

[24] Joakim V , Barbara W .Constructing hermeneutical relations: a postphenomenological inquiry into immersive VR memory palaces[J].Virtual reality, 2023, 27(4):3239-3258.