www.cad-journal.net
Computer-Aided Design AND APPLICATIONS

Application and Innovation of Virtual Reality Technology in Architectural Design and Visualization

Yimin Song[1] and Shengneng Guo[2]

[1]Academy of Art and Design, AnHui University of Technology, Maanshan, AnHui 243032, China, symnj8@ahut.edu.cn
[2]Academy of Art and Design, AnHui University of Technology, Maanshan, AnHui 243032, China, gsn1986@ahut.edu.cn

Corresponding author: Shengneng Guo, gsn1986@ahut.edu.cn

Abstract. The innovative optimization of current architectural design requires the improvement of computer-aided technology (CAD). In order to improve architectural design, this article conducted CAD visualization analysis of architectural design and optimized it based on the original architectural design innovation. In view of this situation, this study makes an in-depth analysis of the application of virtual reality in architecture, and makes some improvements and innovations. Firstly, the orthogonal rate projective iterative transformation algorithm was used to establish a 3D dynamic visualization model for buildings, which realized the dynamic modeling of the whole design process of buildings. Secondly, the multi-site capture matrix and CAD database are used to track and simulate the building, and the appropriate model set is selected in CAD to conduct real-time tracking modeling and self-correction of the building, so as to achieve the differential analysis of different forms of buildings. Finally, the multi-site correction based virtual reality technology is integrated with the multi-site correction mode to realize the dynamic adjustment of the architectural scheme, and the multi-site analysis mode of CAD is integrated with the visual simulation results to achieve the final optimization of the scheme. Experimental analysis shows that this method can effectively improve the efficiency of architectural design and visualization.

Keywords: Architectural Design; Virtual Reality Technology; Proportional Orthogonal Projection Iterative Transformation Algorithm; Visualization
DOI: https://doi.org/10.14733/cadaps.2023.S13.26-37

1 INTRODUCTION

Virtual reality technology mainly refers to building a simulated environment in the computer, obtaining information in the virtual environment through various sensors, and integrating the information at the same time, so as to realize the perception of the virtual environment. The feature of virtual reality technology is that it can simulate the interaction between human and computer, and on this basis, it can simulate the interaction between human and computer. Virtual reality technology has a wide range of applications in construction, which can simulate the construction process, improve construction efficiency and safety. Bashabsheh et al. [1] developed VR technology for construction. This technology will improve construction efficiency and safety, reduce errors and losses during construction. At present, in the research process of virtual reality technology in our country, the study of virtual reality technology is mainly realized through three-dimensional modeling technology, human-computer interaction technology and image processing technology. During the design work, architectural designers will comprehensively consider the function, use requirements, appearance and project cost of buildings. Computer aided design optimization can also improve the visualization level of architectural design. Berseth et al. [2] presented their design solutions more intuitively by using 3D modeling and virtual reality technology. And this design can provide customers or other designers with a deeper understanding of their design intentions. However, virtual reality technology can simulate buildings and quickly and accurately find possible problems in the construction process of buildings, providing effective basis for subsequent projects. On the other hand, China has also carried out application research on visualization of architectural design combined with virtual reality technology, and applied data model databases of a certain scale, such as the western adaptive architectural design model based on multidimensional strategic analysis thinking. In this context, this paper studies the application and innovation of virtual reality technology in architectural design and visualization. Banaei et al. [3] analyzed the emotional impact of two-dimensional architectural forms under different image clusters on residents. This technology utilizes CAD augmented reality technology to focus on individual differences among residents and simulate different indoor areas previously constructed. The results indicate that there are differences between the architectural forms under virtualization and the emotional states of residents, and the results of creating clusters of different architectural forms are also different. Dounas et al. [4] have extensively considered blockchain in their construction projects. It optimizes the framework for prototype validation through BIM design integrated with blockchain mechanisms.

The innovation point of this paper is to propose an integrated model of architectural design and visualization based on the iterative transformation algorithm of proportional orthogonal projection. Combined with virtual reality technology, this paper studies the application of virtual reality technology and CAD model in architectural design visualization, and realizes self-adaptive visualization classification and correction according to different target three-dimensional architectural models. Then the engineering application based on adaptive strategic thinking is realized, which effectively ensures the sense of participation and experience of different buildings in the design process.

This article analyzes the overall framework and research of architectural design visualization. The second part summarizes the application of virtual reality technology and the current research status of architectural design and visualization at home and abroad. In the third part, DDT dynamic visualization model based on iterative transformation algorithm of proportional orthogonal projection in virtual reality technology was constructed. Improved iterative transformation algorithm of proportional orthogonal projection under multi-CAD architecture was adopted to construct cross-level evaluation index system of different virtual reality technology and architectural design excellence. In the fourth part, the visual model of architectural design constructed in this paper is simulated and tested, and the results are analyzed and the conclusion is drawn.

2 RELATED WORK

Entezari et al. [5] demonstrated how the architectural design of 3D printing brackets improves in vivo outcomes. Research also shows that the bimodal pore expansion structure with alternating macropores and micropores significantly enhances the volume and function of new bones. Virtual design architecture education typically uses virtual reality technology and 3D modeling software, allowing students to conduct architectural design and planning in a virtual environment. Ergan et al. [6] integrated a virtual reality architecture design network. Configure biometric sensors from the building environment into the building design feature set to validate experiments to quantify stress. Its research attempts to explain the anxiety in the visualization laboratory of architectural design features. Han et al. [7] use different architectural design software to create different types of buildings, and can observe views from different angles and heights in a virtual environment. Huang et al. [8] analyzed building information modeling in mixed reality (MR) based on both CAD hardware and software aspects. It compares the digital information type tracking ability of VR devices in building construction. The results indicate that although virtual reality has strong capabilities in digital building environment planning and analysis, its functionality in building construction needs to be improved. Higuera et al. [9] introduced a framework for understanding virtual reality building environments based on neuroscience technology. By exemplifying the augmented reality virtual architecture in this area, the environmental model of neural architecture was analyzed. Iranmanesh and Onur [10] use virtual reality technology to enable students to observe different angles and heights of views in a virtual environment, allowing them to have a more intuitive understanding of the structure and function of buildings. Ko [11] has improved the efficiency and accuracy of architectural design through CAD. More accurate prediction and simulation of building performance, including the use of computer models for precise calculation and simulation of building materials. Check the stability and strength of the building structure, predict the use of internal space in the building, and so on. These technologies can help designers better understand the performance of buildings, optimize architectural design, and create more practical, beautiful, and efficient buildings. Pan et al. [12] utilized CAD and CAM technology to achieve automated production, reducing manual operations in the production process and improving production efficiency. These technologies can also make the production process more precise, avoid production errors, and improve product quality. In order to improve building quality, Roman et al. [13] utilized CAD and CAM technology to achieve precise building design and planning, avoiding structural errors and losses, and thereby improving building quality. These technologies can also make the production process more efficient, avoid waste in the production process, and improve production efficiency. Stojanovski et al. [14] believe that artificial intelligence and generation algorithms can enable designers to more accurately predict and simulate the performance of buildings. These technologies can help designers better understand the performance of buildings, optimize architectural design, and create more practical, beautiful, and efficient buildings. Safikhani et al. [15] discussed the digital application transformation of immersive virtual reality, which requires the use of head mounted displays (HMDs) to access resource management in the field of construction engineering. By constructing a building information model, it has strengthened the resolution of obstacles in construction management and operational issues. Tytarenko et al. [16] utilized digital carving and printing techniques to create models of historical relics. This technology can convert 3D models into digital files, and then use a CNC engraving machine or 3D printer to create the model. This method can greatly reduce production time and cost, and can produce higher precision models. In virtual reality modern urban landscape design, Wang [17] uses virtual reality technology to create and present three-dimensional models of urban landscapes. These models can include buildings, roads, parks, rivers, and so on. Through virtual reality technology, designers can roam and interact in virtual spaces to better understand and plan urban spaces. Wu et al. [18] conducted precise 3D point cloud and 2D CAD graphic symmetry design. Present sensory effects such as sound, odor, and light of urban landscapes through virtual reality technology. These effects can help designers better understand and plan urban spaces, and can bring a more immersive experience to the audience. Yi [19] conducted a morphological analysis of residential monitoring in a three-dimensional building environment and visualized the design and simulation of building operation forms.

3 METHODOLOGY

3.1 Application Ideas of POSIT Algorithm and DDT Dynamic Visualization Model in Architectural Design and Visualization

DDT dynamic visualization model is a commonly used model for real-time analysis and modeling of dynamic data, which can realize online modeling of data with low error. In the process of fusion and visualization of target data, DDT dynamic visualization model mainly consists of two steps: one is feature analysis of input data; the other is filling and free planning of classified data based on feature analysis results. After the combination of POSIT algorithm and DDT dynamic visualization model, different 3D modeling data can be improved and the degree of freedom can be improved better, and different architectural models can be designed and classified according to their internal correlation. The visualization principle of POSIT algorithm and DDT dynamic visualization model in the architectural design process is shown in Figure 1.

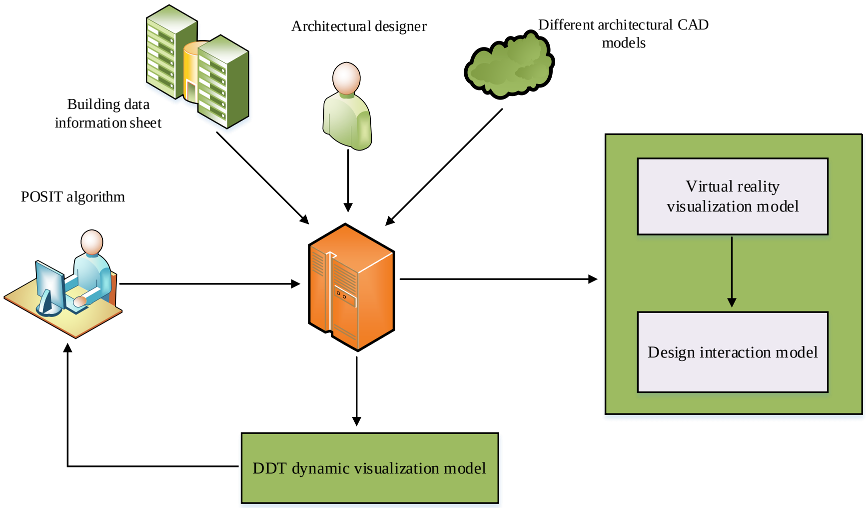

Figure 1: POSIT algorithm and DDT dynamic visualization model in the process of architectural design.

3.2 Dynamic Fitting Capture Process of Virtual Reality Technology in Architectural Visualization Model

The key of architectural design visualization lies in how to realize real-time visualization of data according to the perfect dynamic capture scheme, and one of the core problems of dynamic capture technology is how to accurately capture the model, and the capture result directly affects the reconstruction and visualization effect of the architectural design system behind. Therefore, a multi-fitting function and a dynamic unstable capture function are introduced in this study, whose expressions are respectively:

$$F(u)=\frac{u^3+u^k+u^\lambda+uk}{u^2+k^2+\lambda k} \tag{1}$$

$$G(u)=1+\sqrt{\frac{\lambda u^3+uk^k+u\lambda^\lambda+uk\lambda}{u^2+k^2+\lambda k}} \tag{2}$$

In the formula, u represents different architectural design types, k represents different dynamic capture data sets, and λ represents standard reference compensation value.

When the multi-fitting function and the dynamic unstable capture function classify different building data, the corresponding function expression of the height visualization model is as follows:

$$H(u)=\frac{\sqrt{\dfrac{\lambda u^3+uk^k+u\lambda^\lambda+uk\lambda}{u^2\lambda k+uk^2\lambda^{-1}}}}{\lambda+u+k} \tag{3}$$

At this time, the above calculation results can realize the visualization of multidimensional grouping in the process of architectural design. The corresponding first-order results are as follows:

$$F'(u+k)=uk+\frac{\sqrt{\dfrac{u^3+u^k+u^\lambda+uk}{u^2+k^2+\lambda k}}}{1+\lambda k} \tag{4}$$

$$G'(u+k)=\frac{1+\sqrt{\dfrac{\lambda u^3+uk^k+u\lambda^\lambda+uk\lambda}{u^2+k^2+\lambda k}}}{u+k+\lambda} \tag{5}$$

Then the hierarchical relationship of dynamic virtual reality function can be calculated, and its discriminant is:

$$H'(uk)=\frac{1+\sqrt{\dfrac{\lambda F^3(u)+G^k(k)+u\lambda^\lambda+uk\lambda}{u^2+k^2+\lambda k}}}{F^3(uk)+G^k(uk)} \tag{6}$$

In the formula, u represents different architectural design types, k represents different dynamic capture data sets, and λ represents standard reference compensation value. The above process diagram of dynamic capture of building data is shown in Figure 2.

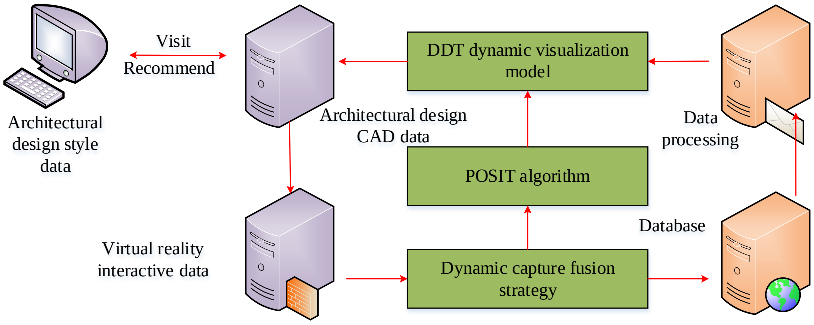

Figure 2: The process diagram of dynamic capture of building data.

3.3 Quantitative Dynamic Simulation Analysis of Virtual Reality Technology in the Process of Architectural Design and Visualization

When using virtual reality technology to capture architectural design model and dynamic visualization simulation analysis, the building data model should be preprocessed first. Preprocessing mainly includes the target of architectural design, maximum three-dimensional coordinate parameters, three-dimensional inflection point, parallelism and other relevant data pre-processing.

In the first step, DDT dynamic visualization model was adopted to realize the coordinate transformation of building data information in the CAD database. The simplest method was to convert the model coordinate system into the sphere coordinate system. In this study, rotation matrix was adopted to mark the rotation axis of the model:

$$J(u)=\frac{\sqrt{\frac{1}{u^2+k^2+\lambda k}}}{F^3(uk)+G^k(uk)} \tag{7}$$

$$Z(u)=\frac{uk\lambda}{\lambda F^{\lambda k}(uk)+G^{\lambda u}(uk)} \tag{8}$$

The second step requires preprocessing and unified analysis of the different inflection points of the architectural design model and the positions in the CAD database, that is, the number of vertices on each edge is added to the three-dimensional diagram of the CAD database, and the vertices are marked in the corresponding three-dimensional visualization grid of the architectural design. At this time, the expressions of the corresponding vertex marking function and CAD database matching function are respectively:

$$X(u)=\frac{\lambda}{uk}\sqrt{\frac{H(u)+F(u)}{u^2+k^2+\lambda k}} \tag{9}$$

$$C(u)=\sqrt{\frac{F^{\lambda k}(u)+G^{\lambda u}(u)}{\lambda+u+k}} \tag{10}$$

The third step is to divide the three-dimensional visualization boundary in the grid into three parts according to the marker, among which there are two edges for dynamic capture modeling of the building. The coordinates of the two edges are parallel to each other (that is, the coordinates of at least one dimension are the same). Therefore, the self-stable first-order expression of the vertex marker function and the CAD database matching function at this time is:

$$X'(u)=\frac{\lambda+u+k}{uk\lambda}+\sqrt{\frac{ukH'(u)}{u^2+k^2+\lambda}} \tag{11}$$

$$C'(u)=\frac{uk\lambda}{u+k+\lambda^2}+\frac{\sqrt{F'(u)+G'(u)}}{\lambda^2+ku^2} \tag{12}$$

In the formula, u represents different architectural design types, k represents different dynamic capture data sets, and λ represents standard reference compensation value.

At this time, according to the self-stabilized first-order function judgment, its dynamic capture method of building design and visualization based on virtual reality technology, and the image output after simulation combined with the improved DDT dynamic visualization model are shown in Figure 3. Combined with the image information in Figure 3, DDT dynamic visualization model has different discriminant priorities for different construction design data, and has certain representation classification rules, because virtual reality technology will analyze the data information captured dynamically in the process of building design and visualization. And according to its inherent data difference and dynamic classification group to realize the feature analysis, and then divide the priority of different weights, and then after setting one-time verification analysis strategy, and then realize the building data corner point and map compilation, and then realize the visual dynamic modeling process, so as to ensure the efficiency of dynamic visual modeling. It can also ensure the accuracy of modeling and further improve the quality of visual modeling of construction design.

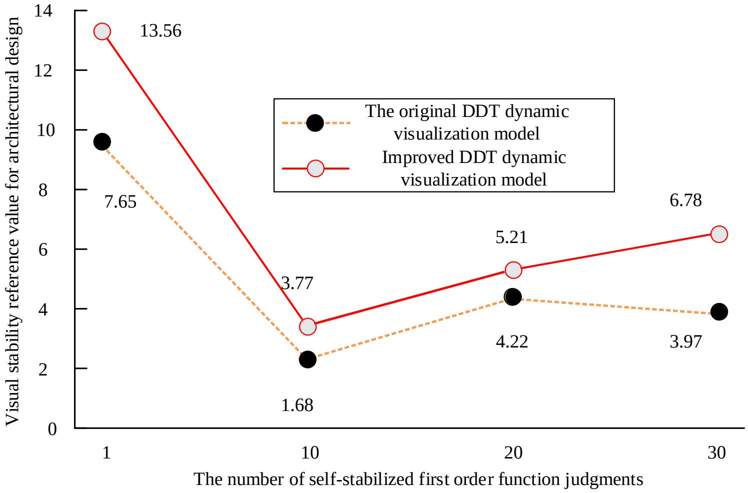

Figure 3: Combined with the improved DDT dynamic visualization model, the image output was simulated.

3.4 Simulation Design of DDT Dynamic Visualization Model Based on Virtual Reality Technology and Posit Algorithm

Firstly, dynamic capture modeling of architectural design model is carried out according to the mentioned POSIT algorithm, and high-dimensional classification and dynamic capture of architectural design are realized according to the models in different CAD databases. Moreover, the capture results of any vertex of architectural design relevance can be used as the data of dynamic real-time visualization model constraint processing. Therefore, this method can realize efficient classification before the model is deformed. At this time, the expression of CAD database update function and architectural design visual update function is as follows:

$$V(u)=\sqrt{\frac{uk\lambda^2}{u^2H'(u)+k^2H'(k)+\lambda}} \tag{13}$$

$$B(u)=\frac{\sqrt{\lambda F'(uk)+kG'(\lambda u)}}{\lambda^2F(uk)+ku^2G(u)} \tag{14}$$

Secondly, the iterative transformation algorithm of proportional orthogonal projection divides the existing whole grid of architectural feature markers into many small building grids of different dimension data sets, and the small grids are associated with different architectural design networks and reference nodes in CAD database. Among them, each different type of grid contains the multidimensional information classification of the entire architectural design model, thus realizing the three-dimensional modeling and visualization process of the entire architectural design.

Finally, as the above CAD database update function and architectural design visual update function have relatively good numerical stability, this study chooses to use the combination judgment function to calculate the Euler Angle needed in the process of architectural design. The expression of the third-order combination judgment function is as follows:

$$N(u+k)=\frac{1+\lambda^2}{uk^2V(u+k)+ku^2C(u+k)} \tag{15}$$

In the formula, u represents different architectural design types, k represents different dynamic capture data sets, and λ represents standard reference compensation value.

Specifically, DDT dynamic visualization model first takes the actual distance between the captured object involved in the architectural design process and the virtual building plane, and carries out equal-fraction interpolation according to the standard reference value in the CAD database, and then takes the interpolated distance as the parameter of the combination judgment function. Then POSIT algorithm calculated the difference Angle between each corresponding captured object and virtual visualization plane in the design process of the building according to the given coordinate position, and further used the three-dimensional model in the virtual reality environment to carry out interactive operation in Unity3D according to the difference Angle, so as to complete the corresponding visual dynamic analysis. However, because the third-order combinatorial judgment function has good local smoothness, a more accurate result can be obtained when Euler Angle is calculated. Therefore, in order to verify the correctness and feasibility of our method, this study first conducted a simulation test on a two-dimensional object. In the process of testing, three different visualization methods of architectural design are used to calculate the Euler Angle required in the process of architectural design, and through the comparative analysis of the test results, it can be seen that the use of third-order combination judgment function to calculate the Euler Angle involved in the process of three-dimensional visualization of architectural design has great advantages in speed and accuracy. Therefore, dynamic requirements for visualization can be well met. The routine analysis results of different types of architectural design and visualization process are shown in Figure 4, and the optimized results are shown in Figure 5.

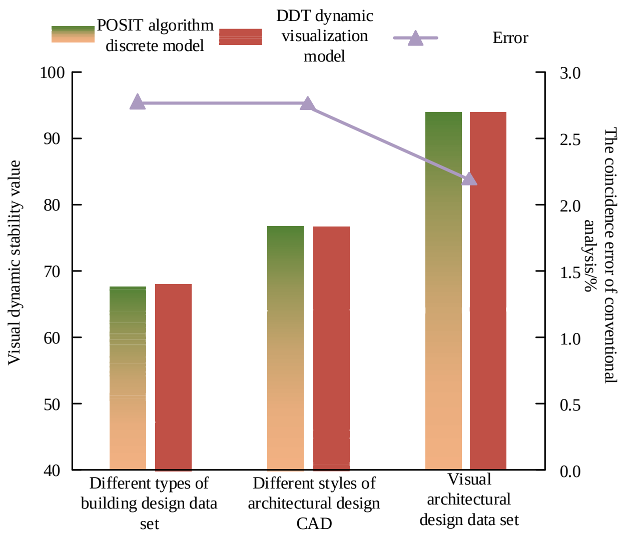

Figure 4: Results of routine analysis of different types of architectural design and visualization processes.

As can be seen from Figures. 4 and 5, DDT dynamic visualization model based on virtual reality technology and POSIT algorithm can well standardize and improve different types of architectural design models based on visualization strategies. Therefore, when designing different architectural models, DDT will show the characteristics and decision values of different strategies. As a result, different types of data sets will present different change rules, so their internal correlation will be greatly different, which will be presented in a visual way (as can be seen from the curve change rules in the figure).

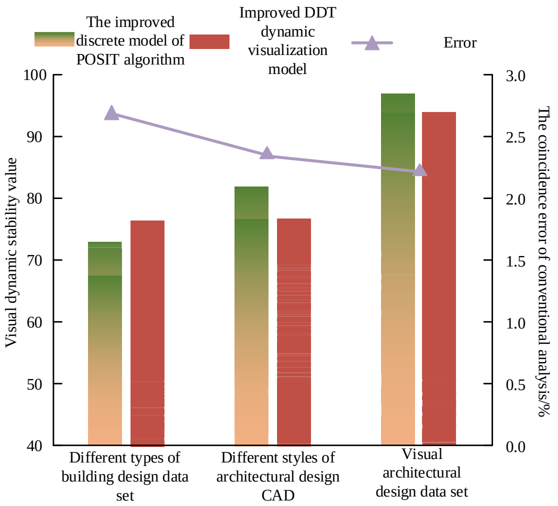

Figure 5: The optimized model is used to analyze the routine results of different types of architectural design and visualization processes.

4 RESULT ANALYSIS AND DISCUSSION

4.1 Experimental Design Process of Virtual Reality Technology in Architectural Design and Visualization Application

In this experiment, VR modeling software, CAD database model and VRML modeling software are mainly used to conduct confirmatory experiments on architectural design and visualization. VR modeling software includes 3DMax, Unity3D and Culture3D, among which Unity3D is a cross-platform 3D modeling software. Before the experiment, this study first used Virtual Reality software to build an online CAD model of the target building, and imported it into Autodesk Pro/E for material mapping, lighting rendering and other processing, so as to realize the virtual restoration of the architectural design process. After that, the visual architectural design model was imported into Unity3D for optimization and dynamic visualization model was generated. After rendering the dynamic visualization model, the combination of Autodesk Pro/E and Unity3D software was used to realize the online construction of virtual reality environment. Finally, the three-dimensional model in the virtual reality environment was used for interactive operation in Unity3D, and DDT dynamic visualization model was used to zoom in and out the details of the building. Through the above process, the application of virtual reality technology to architectural design can realize the interaction and display of architectural design concept, spatial form, detail decoration and other aspects. In this process, the DDT dynamic visualization model based on virtual reality technology and POSIT algorithm applied to different architectural designs and the corresponding experimental results of the visualization scheme are shown in Figure 6.

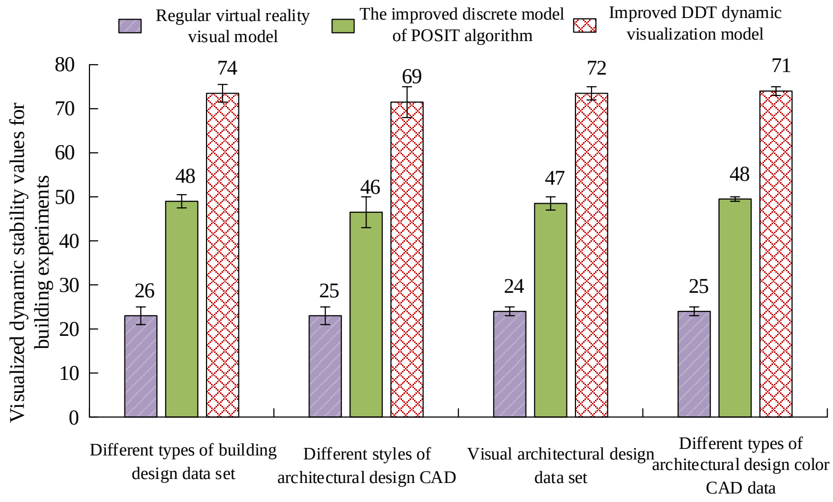

Figure 6: Experimental results corresponding to different architectural designs and visualization schemes.

4.2 Experimental Results and Analysis

Figure 7 shows the algorithm analysis of the architectural model of the experimental results. It displays visualization results under different building template states.

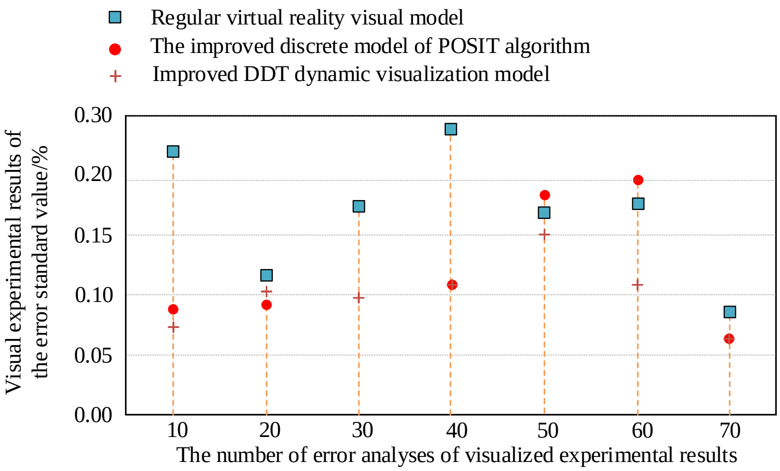

Figure 7: The error analysis of the experiment results of visualization of different types of building formwork.

As can be seen from the above two experimental results, the experimental results of virtual reality technology in architectural design are mainly reflected in the following aspects: (1) Visual interaction models based on virtual reality technology can intuitively present the characteristics, appearance, materials and other information of different types of buildings, which is conducive to better scheme decision-making for designers. (2) Virtual reality technology can visually present the internal space of buildings in three-dimensional space, so that people have a more intuitive, three-dimensional and real understanding of the internal space of buildings. Virtual reality technology provides an interactive environment for designers to talk with space, promotes the interaction between architectural design and people, and shows high accuracy of interaction in the process of experiment. (3) Virtual reality technology can realize the visualization of the spatial form and aesthetic value of buildings, and the error is very low, and the visualization speed is very high.

5 CONCLUSION

Virtual reality technology and CAD technology can present architectural design solutions in virtual spaces, enabling designers to interact and better understand and plan architectural spaces. This method can greatly improve the efficiency and quality of architectural design. In order to further innovate and optimize the analysis of architectural CAD design, this article conducts an in-depth analysis of the application of virtual reality in architecture, and made some improvements and innovations to it. Firstly, the orthogonal rate projective iterative transformation algorithm was used to establish a 3D dynamic visualization model for buildings, which realized the dynamic modeling of the whole design process of buildings. Secondly, the multi-site capture matrix and CAD database are used to track and simulate the building, and the appropriate model set is selected in CAD to conduct real-time modeling of the building, so as to achieve the difference analysis of different forms of buildings. Finally, the multi-site correction based virtual reality technology is integrated with the multi-site correction mode to realize the dynamic modification of the architectural scheme. Moreover, the multi-site analysis mode of CAD is used to integrate the scheme with the visual simulation results to realize the dynamic modification of the scheme. The experimental results show that this method has a good effect. However, this study only considers the application of virtual reality technology in architectural design and visualization, and does not consider the influence of external lighting and other factors required in the actual use of buildings, so a more in-depth study can be carried out.

Yimin Song, https://orcid.org/0009-0001-0852-7064
Shengneng Guo, https://orcid.org/0000-0002-3294-2890

REFERENCES

[1] Bashabsheh, A.-K.; Alzoubi, H.-H.; Ali, M.-Z.: The application of virtual reality technology in architectural pedagogy for building constructions, Alexandria Engineering Journal, 58(2), 2019, 713-723. https://doi.org/10.1016/j.aej.2019.06.002
[2] Berseth, G.; Haworth, B.; Usman, M.; Schaumann, D.; Khayatkhoei, M.; Kapadia, M.; Faloutsos, P.: Interactive architectural design with diverse solution exploration, IEEE Transactions on Visualization and Computer Graphics, 27(1), 2019, 111-124. https://doi.org/10.1109/TVCG.2019.2938961
[3] Banaei, M.; Ahmadi, A.; Gramann, K.; Hatami, J.: Emotional evaluation of architectural interior forms based on personality differences using virtual reality, Frontiers of Architectural Research, 9(1), 2020, 138-147. https://doi.org/10.1016/j.foar.2019.07.005
[4] Dounas, T.; Lombardi, D.; Jabi, W.: Framework for de-centralised architectural design BIM and Blockchain integration, International Journal of Architectural Computing, 19(2), 2021, 157-173. https://doi.org/10.77/478077120963376
[5] Entezari, A.; Roohani, I.; Li, G.; Dunstan, C.-R.; Rognon, P.; Li, Q.; Zreiqat, H.: Architectural design of 3D printed scaffolds controls the volume and functionality of newly formed bone, Advanced healthcare materials, 8(1), 2019, 1801353. https://doi.org/10.1002/adhm.201801353
[6] Ergan, S.; Radwan, A.; Zou, Z.; Tseng, H.-A.; Han, X.: Quantifying human experience in architectural spaces with integrated virtual reality and body sensor networks, Journal of

Computing in Civil Engineering, 33(2), 2019, 04018062. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000812
[7] Han, Y.-S.; Lee, J.; Lee, J.; Lee, W.; Lee, K.: 3D CAD data extraction and conversion for application of augmented/virtual reality to the construction of ships and offshore structures, International Journal of Computer Integrated Manufacturing, 32(7), 2019, 658-668. https://doi.org/10.1080/0951192X.2019.1599440
[8] Huang, Y.; Shakya, S.; Odeleye, T.: Comparing the functionality between virtual reality and mixed reality for architecture and construction uses, Journal of Civil Engineering and Architecture, 13(1), 2019, 409-414. https://doi.org/10.17265/1934-7359/2019.07.001
[9] Higuera, T.-J.-L.; Llinares, C.; Macagno, E.: The cognitive-emotional design and study of architectural space: A scoping review of neuroarchitecture and its precursor approaches, Sensors, 21(6), 2021, 2193. https://doi.org/10.3390/s21062193
[10] Iranmanesh, A.; Onur, Z.: Mandatory virtual design studio for all: Exploring the transformations of architectural education amidst the global pandemic, International Journal of Art & Design Education, 40(1), 2021, 251-267. https://doi.org/10.1111/jade.12350
[11] Ko, C.-H.: Constraints and limitations of concrete 3D printing in architecture, Journal of Engineering, Design and Technology, 20(5), 2022, 1334-1348. https://doi.org/10.1108/JEDT-11-2020-0456
[12] Pane, Y.; Arbo, M.-H.; Aertbeliën, E.; Decré, W.: A system architecture for cad-based robotic assembly with sensor-based skills, IEEE Transactions on Automation Science and Engineering, 17(3), 2020, 1237-1249. https://doi.org/10.1080/0951192X.2019.1599440
[13] Roman, A.; Andrii, S.; Galyna, R.; Honcharenko, T.; Iurii, C.; Hanna, S.: Integration of data flows of the construction project life cycle to create a digital enterprise based on building information modeling, International Journal of Emerging Technology and Advanced Engineering, 12(1), 2022, 40-50. https://doi.org/10.46338/ijetae0122_05
[14] Stojanovski, T.; Partanen, J.; Samuels, I.; Sanders, P.; Peters, C.: City information modelling (CIM) and digitizing urban design practices, Built Environment, 46(4), 2020, 637-646. https://doi.org/10.2148/benv.46.4.637
[15] Safikhani, S.; Keller, S.; Schweiger, G.; Pirker, J.: Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review, International Journal of Digital Earth, 15(1), 2022, 503-526. https://doi.org/10.1080/17538947.2022.2038291
[16] Tytarenko, I.; Pavlenko, I.; Dreval, I.: 3D Modeling of a Virtual Built Environment Using Digital Tools: Kilburun Fortress Case Study, Applied Sciences, 13(3), 2023, 1577. https://doi.org/10.3390/app13031577
[17] Wang, M.: Research on urban architecture landscape design based on virtual reality technology, In Journal of Physics: Conference Series, 1904(1), 2021, 012013. https://doi.org/10.1088/1742-6596/1904/1/012013
[18] Wu, Y.; Shang, J.; Xue, F.: RegARD: symmetry-based coarse registration of smartphone's colorful point clouds with CAD drawings for low-cost digital twin buildings, Remote Sensing, 13(10), 2021, 1882. https://doi.org/10.3390/rs13101882
[19] Yi, H.: Visualized co-simulation of adaptive human behavior and dynamic building performance: an agent-based model (ABM) and artificial intelligence (AI) approach for smart architectural design, Sustainability, 12(16), 2020, 6672. https://doi.org/10.3390/su12166672