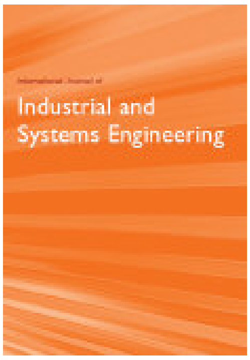

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Research on immersive experience of packaging design based on virtual reality and semantic segmentation algorithm

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Abstract: The rapid advancement of digital technology is revolutionising packaging design through the integration of virtual reality (VR) and semantic segmentation. Traditional two-dimensional design methods are inadequate for accurately conveying three-dimensional structures, textures, and product intricacies, This study presents an immersive packaging design system that leverages VR and deep learning-based semantic segmentation to address these limitations. The system was developed through a structured approach involving framework analysis, extensive data preparation, model training, and the creation of interactive VR environments. A user study with 50 participants demonstrated significant improvements in comprehension (average score: 4.2 vs. 3.0), satisfaction (4.0 vs. 2.8), engagement (4.1 vs. 2.5), and task efficiency (15 minutes to 10 minutes). An empirical case with a beverage brand further validated its effectiveness, showing increased consumer satisfaction, understanding, engagement, purchase intent. These results underscore the system's potential to enable intelligent, personalised, and immersive packaging design experiences.

Keywords: virtual reality; VR; semantic segmentation algorithms; package design; immersive experiences.

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1 Introduction

With the leaping progress of science and technology, VR technology is becoming more and more mature, and the space of application is getting bigger and bigger, which brings customers immersive experience. In packaging design, the designer can only use the traditional flat two-dimensional display form, it is difficult to display the three-dimensional spatial shape of the packaging, texture, product information, the customer experience is also limited, the semantic segmentation algorithm in the field of computer vision is a very important technical method, which can classify each pixel in the image, which is very helpful for the completion of the identification and analysis of the packaging elements in the virtual reality (VR) environment. The combination of VR and semantic segmentation algorithms in packaging design enables customers to have an immersive, vivid and interactive experience. Through VR, customers can experience the three-dimensional shape of the packaging space, observe the details of the packaging in an all-round way, and simulate the process of using the packaging products; the semantic segmentation algorithm accurately identifies and segments each element in the packaging image, providing a strong technical basis for personalised customisation, intelligent interaction, and so on. This can improve customer satisfaction and participation in packaging design, but also helps enterprises to bring more innovative space and competitive chips, and promote the packaging design industry to intelligent, personalised, immersive development.

In foreign countries, the research on the application of VR technology in packaging design started earlier, and some famous enterprises have begun to apply VR technology to product packaging display and marketing (Li and Zhao, 2024) pointed out that Coca-Cola had launched a packaging experience based on VR technology, and the user can experience the Coca-Cola brand culture and marketing by wearing VR equipment. Coca-Cola's brand culture and product charm (Yu et al., 2024) for the packaging design based on VR technology, its application effect in packaging design, user experience, and other research, put forward a series of innovative methods and theoretical models based on VR technology packaging design. Da Mutten et al. (2024) pointed out that semantic design is the most effective way of designing packaging. It pointed out that, in terms of semantic segmentation algorithm research, foreign countries are in the leading position, and new algorithms and models are constantly proposed, such as MaskR-CNN and other algorithms, the accuracy as well as the efficiency of which has been substantially improved, and the application of this type of algorithms in the field of packaging image analysis and other fields has also been done a lot of research. In China, with the popularisation of VR technology, the development of computer vision technology and the rapid development of computer science, the country has also begun to carry out a lot of research on the application of VR technology in packaging design, exploring how to utilise VR technology to enhance the innovativeness of packaging design and improve the user experience.

Wang et al. (2025) concluded that in the enterprise, there are also enterprises that have begun to try to use VR technology applied in packaging design and marketing, such as white wine enterprises use VR technology to demonstrate the history and culture of the enterprise and brewing process, which increases the consumer's awareness and goodwill towards the enterprise. In terms of semantic segmentation algorithm research, Zhao et al. (2022) keep up with the international frontier promptly to carry out algorithmic improvement. Algorithmic expansion of the research, optimisation of algorithmic improvement for a specific packaging image dataset have achieved certain results. At present, there is still a lack of foreign research on semantic segmentation algorithms in packaging design; domestically, there is no systematic exploration of the deep integration of VR and semantic segmentation algorithms in packaging design, especially in how to use semantic segmentation algorithms to achieve intelligent interaction and personalised customisation of packaging design in the context of VR, which still needs to be improved and deepened.

1.1 Literature review

Chen and Mu (2024) investigated the amalgamation of computer-aided design (CAD) with multimedia sensing and VR in packaging design. They demonstrated that multimedia components improved engagement, whilst sensing technology facilitated effective pattern identification. VR simulations enhanced design efficiency and user engagement, facilitating the digital and intelligent advancement of the packaging sector. Luo et al. (2024) conducted a review of semantic segmentation techniques in agricultural picture analysis, evaluating both conventional and deep learning methodologies. They emphasised potential in crop classification, pest detection, and crop cover analysis while recognising significant obstacles like inadequate generalisation and a scarcity of labelled data. They proposed data augmentation and multimodal integration to overcome these issues. Their research provided significant insights for advancing agricultural automation via refined segmentation methods. Hao et al. (2023) devised a multi-objective semantic segmentation system with an enhanced U-Net, aimed at construction zones for transport facilities. A UAV- based multi-class dataset and an innovative virtual data augmentation technique were introduced, along with transfer learning, to improve segmentation accuracy. Their model attained an accuracy of up to 97.56%, proficiently recognising various building aspects. Shi (2023) introduced a product colour matching design methodology that integrates augmented reality with a BP neural network grounded in Kansei engineering.

The method was evaluated in a case study of a soybean milk machine by correlating colour codes with perceptual image assessments. The results validated the method's efficacy in associating emotional imagery with colour matching, illustrating its viability for automated design assistance. Kelley et al. (2024) created a VR-based visualisation pipeline that integrates a VGG-16 deep learning model with immersive analytics to enhance MRI interpretation for neurological diagnosis. The model delineates impacted cerebral regions from FLAIR MRI scans, which are subsequently volumetrically produced and examined in VR via a head-mounted display, facilitating interactive three-dimensional analysis of lesions. This method provides a more intuitive and efficient instrument for medical analysis and treatment. Jin (2023) introduced an AI-driven approach for 3D image creation in packaging design by integrating a confidence propagation-mean shift algorithm with an enhanced Lucas-Kanade optical flow algorithm. This method successfully extracted parallax maps and generated precise 3D pictures, attaining over 99% depth accuracy while minimising computing time. The findings underscore the method's efficacy and promise for economical, high-quality 3D imaging in packaging applications.

Dongdong (2025) implemented an image denoising technique in a VR-based system to improve the clarity and realism of virtual ornamental material environments. The method enhanced image quality through the integration of sensor-based image acquisition and modelling, facilitating more precise material selection based on aesthetic and functional factors. The results indicated the system's capacity to enhance indoor environmental design. Sagayam et al. (2020) created an IoT-based VR game that integrates biofeedback and physical computing to facilitate rehabilitation for a frozen shoulder. The device utilised wearable ultrasonic sensors to monitor mobility, engaging patients in remedial activities via interactive gameplay. Results indicated enhanced patient results, illustrating the efficacy of VR gaming in physical rehabilitation. Hammoud and Lupin (2024) created a CNN-based deep learning model for road detection in autonomous vehicles utilising the KITTI dataset and transfer learning with pre- trained architectures such as ResNet and VGG. Their model surpassed Unet and LinkNet, with a peak F1-score of 0.9909, illustrating its efficacy for precise and dependable road segmentation in ADAS.

1.2 Research gaps and novelties

Despite the extensive application of VR in many design domains, there is a significant deficiency in research on its amalgamation with semantic segmentation algorithms within the realm of packaging design. Current research predominantly emphasises either VR-based visualisation or the implementation of segmentation algorithms independently, neglecting to thoroughly investigate their synergistic potential. Specifically, limited international research has investigated the application of semantic segmentation to improve packaging design in immersive environments, and domestic studies have yet to offer a systematic framework for this integration. The potential of semantic segmentation to facilitate intelligent interaction and personalised customisation in packaging is underexploited, creating a significant void in both scholarly research and practical implementation. This work mitigates these constraints by presenting a comprehensive, immersive package design experience system that intricately blends VR and semantic segmentation techniques. This approach's innovation is its capacity to identify and segregate package components in real time, allowing users to engage dynamically with the packaging inside a very realistic virtual environment. The technology improves user engagement, comprehension, and happiness by integrating precise image analysis with immersive 3D interaction. This integrated framework addresses a significant deficiency in existing design techniques and advances the creation of intelligent, user-centric packaging systems, providing novel opportunities for tailored and efficient product presentation.

1.3 Paper organisation

This document is structured as follows: Section 2 delineates the fundamental technologies that support the study, encompassing VR and semantic segmentation algorithms, and evaluates their potential for integration in packaging design. Section 3 delineates the suggested methodology, encompassing data gathering and preprocessing, the development and training of an enhanced U-Net segmentation model, and the creation of an interactive VR scenario. Section 4 delineates an immersive experience experiment that contrasts the proposed system with conventional 2D approaches on user comprehension, satisfaction, engagement, and work efficiency. Section 5 presents a case study of a beverage brand, demonstrating the system's tangible effect on consumer engagement and purchase intention. Section 6 ultimately concludes the research by encapsulating essential findings and emphasising the potential of the suggested methodology to enhance intelligent, personalised, and immersive packaging design.

2 Related technology principles

2.1 VR technology

VR technology is the use of computers to generate a virtual world of three-dimensional environments, so that the user is in a kind of immersive feeling and provide the user with visual, auditory and tactile all-round stimulation, so that the user has the feeling of being in the realm of reality, and can interact naturally with the objects in the virtual world (Tian et al., 2019). The principle is based on computer graphics, sensor technology, human-computer interaction technology and other aspects. In computer graphics, through the establishment of a three-dimensional model of the virtual scene, the use of rendering technology for real-time rendering of the objects in the scene, to generate realistic images, according to the user's point of view of the change in the rapid update of the screen, to provide a virtual scene that conforms to the visual habits of the human eye; in the aspect of the sensor technology, real-time perception of the user's movement, position, posture and other information, usually used sensors are gyroscopes, Accelerometer, magnetometer, etc., can accurately track the position information of the user's head, hands and other parts, and provide the relevant information to the computer, which adjusts the display of the virtual scene according to the changes in the relevant data, so that the user can interact with the virtual environment. For example, when the user turns his head to watch, the VR equipment can quickly sense and adjust the display screen in the corresponding environment, giving the user a visual effect similar to that in real life when turning his head (Zhang et al., 2023).

VR technology has three characteristics: immersion, interactivity and imagination. Immersion allows users to fully integrate into the virtual environment and feel the real experience. Such as in VR game applications, virtual people or people will be integrated into the virtual world with the thinking and consciousness of real people, so that its users are fully integrated. Interactivity allows users to interact with the virtual world environment, interact with virtual objects and interactive controllers, such as grasping virtual objects, manipulating virtual objects, and manipulating virtual devices. Imagination allows the user to utilise this virtual environment to make associations and imagination, to create and interact freely in the atmosphere of the virtual world. For example, in VR, design can be utilised in which VR design software can be used to design and develop at will (Xinghua et al., 2024). VR technology has been developing rapidly in recent years, and the market size also expands with each passing year, and the comprehensive International Data Corporation (IDC), Omdia, CINNO Research and other organisations' reports can be seen that the global VR market size continues to rise in 2020–2024 (see Table 1). In the hardware VR headset resolution, refresh, field of view angle and other performance continues to improve, HTC Vive Pro 3 as a representative of high-end VR headset, resolution can reach monocular 4K or more, refresh rate of 200 Hz or more, field of view angle of close to 200° greatly improves the user's sense of experience; in the software and content, the VR application is becoming increasingly varied, the content includes games, education, medical, industrial design, etc. (Zhan et al., 2024).

In terms of software and content, there is a growing variety of VR applications, including games, education, medical, industrial design, etc. (Zhan et al., 2024). In the game content, 3A masterpieces are more and more out of the VR version, for players to bring a new game experience; in education, VR technology used in the virtual laboratory establishment, historical scene restoration, etc., to enhance the teaching of the fun and timeliness; in industrial design, designers can apply VR technology for three-dimensional design, simulation of the assembly, etc. to improve the design efficiency, design quality.

Table 1 Global VR market size, 2020–2024 (in USD billion)

Vintages	*Market size*
2020	100
2021	150
2022	220
2023	300
2024	400

2.2 Semantic segmentation algorithm

A semantic segmentation algorithm is an important basic algorithm in the field of computer vision, which aims to assign a class label to each pixel in an image to realise the recognition and segmentation of objects and scenes in an image. The principle of semantic segmentation is to train a deep learning model that autonomously learns image features based on having a large number of pixel-level labelled images and classifies pixels accordingly. The commonly used semantic segmentation models are full convolutional network (FCN), U-Net, Deeplab series, etc. Among them, FCN is to replace the fully connected layer in the traditional CNN with a fully convolutional layer to make it possible to predict the input image of any size and at the same time to generate segmentation results of the same size as the input image (Wang et al., 2024b) FCN consists of an encoder, a decoder, the encoder extracts the high-level semantic features of the image, similar to the feature extraction in the CNN; the decoder consists of a series of up-sampling operations to restore the low-resolution feature map to the original image size by a series of up-sampling operations, and then performs pixel-level classification. The operation formula is as follows.

Let the input image be; after a series of convolution operations and activation functions, the feature map is obtained as formula (1):

$$f_1\left(f_2\left(\cdots f_n(I)\right)\right) \tag{1}$$

included among these f_i denotes the combination of the first convolutional layer and the activation function. In the decoder part, the feature map is upsampled to the original image size by an inverse convolution (also called transposed convolution) operation and classified to get the segmentation result as formula (2)

$$S = g_1\left(g_2\left(\cdots g_m(F)\right)\right) \tag{2}$$

included among these: g_j denotes the combination of the first inverse convolutional layer and the classification operation. During the training process, the model parameters are adjusted by minimising the loss function between the predicted results and the real labels, and the commonly used loss function is the cross-entropy loss function as formula (3):

$$-\sum_{i=1}^{N}\sum_{j=1}^{C} y_{ij} \log\left(\hat{y}_{ij}\right) \tag{3}$$

where is the total number of pixels in the image, is the number of categories, and y_{ij} is the true label (0 or 1) of the i^{th} pixel belonging to class, $\hat{y}_{ij}$ is the probability that the model predicts that the i^{th} pixel belongs to the j^{th} class (Tang et al., 2024). The U-Net model is an improvement of FCN, which uses a U-shaped network structure and adds a hopping connection in the middle of the encoder and decoder, which can combine the low-level detail information and high-level semantic information to improve the segmentation accuracy, especially used in medical image segmentation. The Deeplab series of models use the methods of null convolution and spatial pyramid pooling to increase the sensory field and obtain the multi-scale information of the image information, which is more suitable for the natural scene segmentation task of images.

2.3 Feasibility of combining VR with semantic segmentation algorithms

Combining VR and semantic segmentation algorithms to realise the immersive experience of packaging design has great feasibility. On the one hand, VR technology provides an immersive three-dimensional packaging display environment so that users can truly feel the appearance of the package, the structure of the package, and the use of the package environment, but the ability to automatically identify and analyse the complex elements in the package image is low. On the other hand, the semantic segmentation algorithm automatically identifies and segments the text, pattern, material, and other elements in the packaging image, providing data support for personalised customisation and intelligent interaction in packaging design (Wang et al., 2024a), but it lacks specific immersive experience. Combining the semantic segmentation algorithm with VR can provide more semantics for the packaging model in the VR scene and realise the automatic identification and classification of the elements in the packaging to support the intelligent interaction between the user and the elements in the packaging. For example, when the user can view the package in the VR environment, the semantic segmentation algorithm automatically recognises the text information in the package image and broadcasts the text information by voice according to the user's instruction; the material area is segmented out, and tactile interaction is carried out with different materials (Li et al., 2024).

VR technology will provide a more realistic, immersive experience environment for the application of semantic segmentation algorithms, which can provide real-time inspection and correction for the segmentation results and enhance the user's intelligent interaction with the elements in the package. The results of the semantic segmentation algorithm can be examined and corrected in real time to improve the efficiency of packaging design. At the same time, with the continuous progress of hardware technology, the computational capacity has been improved to make the real- time cooperative operation of VR and semantic segmentation algorithm possible, which lays an important foundation for the deep integration of VR and semantic segmentation algorithm.

3 Packaging design method based on VR and semantic segmentation algorithm

3.1 Data acquisition and preprocessing

Data acquisition is used to support the construction of a packaging design system based on VR+ semantic segmentation algorithm. Data collection sources include collecting packaging images from existing packaging galleries in the market, adopting different product types, styles and design concepts, and collecting packaging images downloaded by web crawlers from various e-commerce platforms, design material websites and professional packaging design websites to ensure the diversity and representativeness of data; The 3D scanner is used to scan the actual packaging material, collect the packaging image, obtain the three-dimensional model data of the packaging, collect and record the shape, size, structural details and other parameters of the packaging; Use user research to obtain user demand for packaging design, preferences, feedback and other data. In the acquisition stage, image acquisition devices, such as high-definition cameras, are used to acquire the packaging images with high resolution and clear details, and provide high-quality data sources for the next step. 3D scanning uses 3D scanners with high precision and large scanning ranges to ensure complete and accurate information acquisition on the packaging.

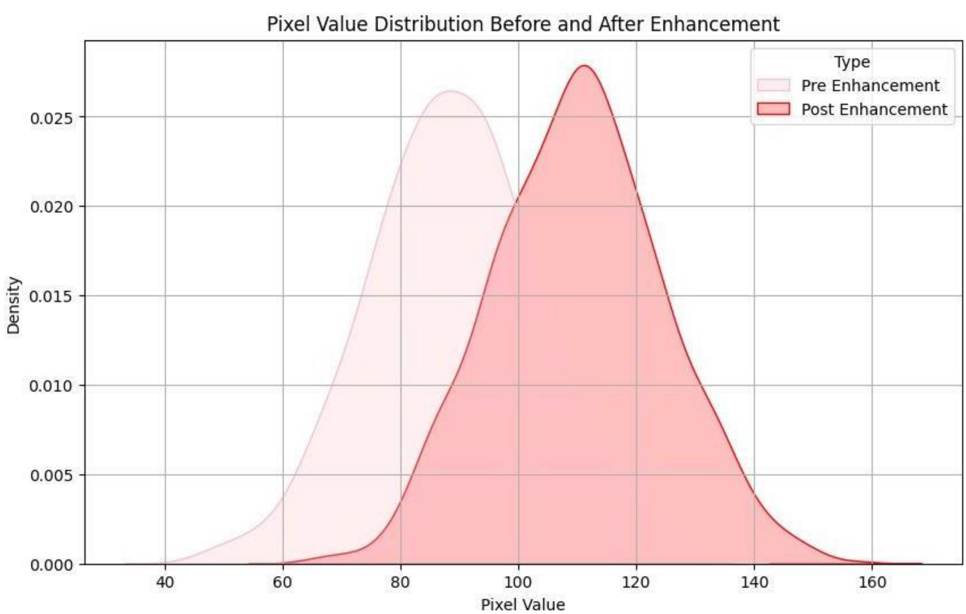
For the collection of packaging images, the image is first enhanced, and the visual effect is improved by adjusting the brightness, contrast and colour saturation of the image so that the font, pattern and other features of the package are easier to identify. A histogram equalisation algorithm was used to adjust the grey distribution of the image and enhance the contrast of the image, as can be seen in Figure 1.

Among them, the cumulative distribution function (CDF) is used to calculate the cumulative frequency of occurrence of each grey value in the image. Next, a filtering algorithm is used to remove the noise interference in the image. The commonly used Gaussian filtering algorithm effectively smooths the image and removes the random noise by weighted averaging the pixel values in the neighbourhood of the image pixels. The mathematical principle is as follows. Let the input image be $I(x, y)$, the output image be $O(x, y)$, the Gaussian filter weight function be $G(x, y, \sigma)$, and the pixel values of the image after Gaussian filtering be described as formula (4) (Tang et al., 2024):

$$O(x, y) = \sum_{m=-k}^{k} \sum_{n=-k}^{k} I(x+m, y+n) \times G(m, n, \sigma) \tag{4}$$

where k is the radius of the filter and σ is the standard deviation of the Gaussian distribution, which determines the degree of smoothing of the filter. Data denoising and streamlining are performed on the packaging model data obtained from 3D scanning to eliminate the noise and redundant data in the scanned data, optimise the model data structure, and improve the data processing efficiency. In the process of streamlining the model, edge folding algorithms are applied to reduce the number of triangular facets of the model and reduce the amount of data under the premise of ensuring that the basic shape and features of the model remain unchanged. Normalisation preprocessing is performed on all data to normalise the amount of data from different sources and in different formats to the same scale and range, so as to facilitate later data analysis and model training. For example, the pixel values in the image data are normalised to the [0, 1] interval, and the coordinate data in the 3D model are normalised to the corresponding range to ensure the consistency and comparability of the data. After the above data acquisition and pre-processing steps, a good quality and standardised data base is provided for the packaging design based on VR and semantic segmentation algorithms, which facilitates the possibility of improving the performance and accuracy of the subsequent models.

Figure 1 Comparison of pixel value distribution before and after packaging image enhancement (see online version for colours)



3.2 Construction and training of semantic segmentation models

In the experiment, by improving the U-Net model as the base model for semantic segmentation, the attention mechanism module is added to the classical U-Net network framework to enhance the focus on the key features of the package image. The attention mechanism module realises automatic learning of the regional importance weights of the image and pays more attention to the key elements of the package, such as brand logo, product name, body pattern and other information, to improve the segmentation accuracy. Specific and detailed settings are made for the selection of network parameters in the model. Define the initial convolution layer convolution kernel size of 3 × 3, step size of 1 and padding of 1 to fully extract image local features. In the encoder, the number of convolution kernels is increased with the increase of network depth, for example, 64 → 128 → 256, in this way to increase the range of sensory field and extract higher-level semantic information; in the decoder part, the inverse convolution layer is used to restore the feature maps to the original image scale, and at the same time the feature maps of the corresponding levels of the encoder are connected to the feature maps of the decoder through jump connections. In the decoder part, the inverse convolutional layer is used to restore the feature map to the original image scale, and at the same time, the feature map of the corresponding level of the encoder is fused with that of the decoder through a hopping connection to fully utilise the image details. The convolutional kernel size of the inverse convolutional layer is 2 × 2 with a step size of 2, which accomplishes the role of up-sampling (Sun, 2024).

The model is trained using a dataset containing a large number of packaged images collected from the market (10,000 in total) and the dataset is divided into training, validation and test sets in the ratio of 8:1:1. Among them, the training set is used to learn the model parameters, the validation set is used to evaluate the model performance and adjust the hyper-parameters during the training process to prevent overfitting, and the test set is used for the final model evaluation. In the training method, the Adam optimiser is selected, the value of learning rate is 0.0001, beta1 takes the value of 0.9, beta2 takes the value of 0.999, epsilon takes the value of 1e-8, and the loss function adopts the weighted combination of cross-entropy loss and Dice loss to better solve the problem of category imbalance so as to improve the segmentation accuracy, in which, the cross-entropy loss is used to Evaluate the deviation of the model's prediction from the real label, dice loss is used to measure the overlap between the segmentation result and the real label, and the two are combined to make the model performance more balanced. The combined loss function *L* is defined as formula (5) (Taheri Gorji et al., 2023).

$$L = \alpha \times CrossEntropyLoss + (1 - \alpha) \times DiceLoss \tag{5}$$

where α is the equilibrium coefficient, set to 0.5. All the training is carried out on a computer equipped with two NVIDIARTX3090 GPUs, and a total of 100 epochs are trained and it records the model's LOSS and ACCURACY on the validation set in the process of training, which is used to judge the training effect of the model. Variation curve of loss value of validation set during model training process can be seen from Figure 2 and curve of validation set accuracy change during model training process can be seen from Figure 3. It can be found that the model's loss in the validation set is gradually decreasing with the iteration of training, and the accuracy is gradually increasing, indicating that the model can effectively learn the features of the packaging image to realise the accurate segmentation of packaging elements. In the early stage of training, the loss decreases faster and the accuracy rises obviously; in the late stage of training, the loss decreases gradually and the accuracy converges, indicating that the model converges.

Figure 2 Variation curve of loss value of validation set during model training process (see online version for colours)

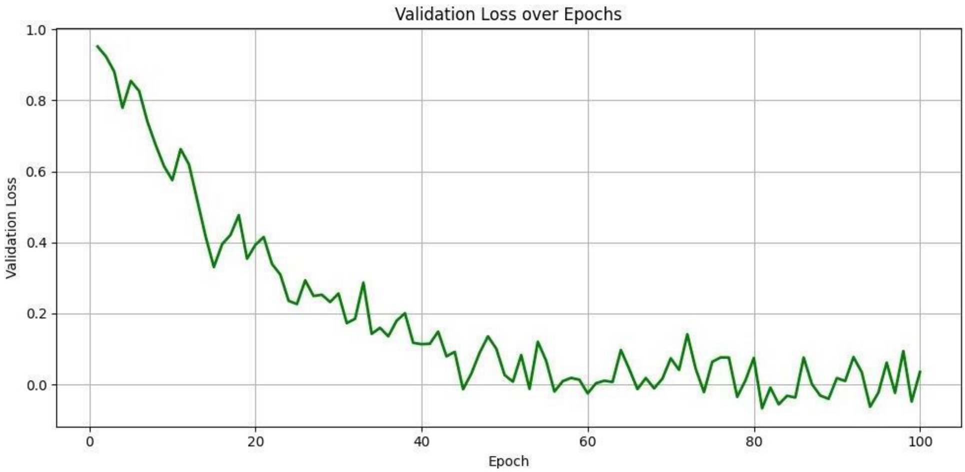
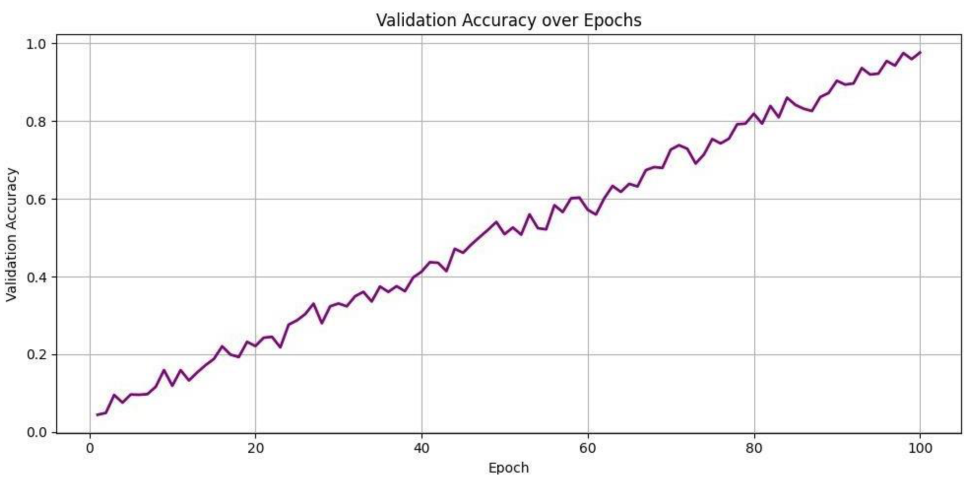


Figure 3 Curve of validation set accuracy change during model training process (see online version for colours)



3.3 VR scene construction and interaction design

With the help of Unity3D engine to build a VR scene, its rich and diverse plug-ins and tools can quickly build a realistic virtual scene. First of all, import the pre-processed 3D model of the packaging and the packaging elements segmented by the semantic segmentation model. Place the 3D model in the virtual scene to the appropriate position, concerning the actual packaging display needs, set the size, direction and position of the model, so that it meets the needs of the user to watch, such as the rectangular shape of the box placed in the centre of the scene, facing the user, the height of the user's line of sight parallel to the user, so that the user can watch the packaging of all sides (Roumaissa and Chaouki, 2025). Virtual scene modelling is used to enhance the realism of the scene. Add lighting, simulate a variety of lighting environments, such as natural ambient light, indoor lighting, etc., through the light brightness, colour temperature, light source projection direction of the different settings, resulting in a realistic light and shadow effect, so that the packaging in a variety of natural environmental light can produce a realistic sense of material; add a virtual display platform, background, etc., to build a perfect virtual display environment, to enhance the sense of realism of the scene; the display platform material can be set to wood, metal, and so on, according to the style of the packaging. Set for wood, metal texture, the background is set according to the theme of packaging style and target audience for different colours and patterns, such as children's food packaging background can be designed according to the characteristics of the product is full of children's cartoon patterns (Huang et al., 2024).

Realise a variety of interactions in the interaction. Utilising the VR handle, users can view the packaging in all directions through the handle. Through the mobile rotation function of the handle, the angle of the package is adjusted, and the details of the package are viewed from different perspectives, such as the top of the head, the bottom, the side, etc., to satisfy the user's comprehensive needs for the package. When the user puts the handle close to the package model, the zoom function will automatically appear, and the user can see the detailed information, such as text patterns on the package, more clearly (Tang et al., 2023). When the user handle touches the elements of the package, such as the brand logo, the program automatically pops up some information windows about the product, the content of which is the brand story, product introduction, etc.; when the user clicks on the open button on the package, it simulates the opening of the package to show the structure of the inside of the package, and the location of the product placement, so that the user intuitively understands the function and role of the package. To realise these interactive functions, corresponding scripts are written in Unity3D, and the corresponding interaction logic is invoked by detecting whether collision events are generated between the handle and the packaging elements.

Among them, ray detection technology is used to determine what element the intersecting element is when the ray shot by the handle intersects with the packaging element, and call the corresponding logic such as the appearance of an information window and playing animation (Fan et al., 2024). By creating a good VR scene and rich interaction methods, the process of experiencing the package design is provided to the user, so that the user can participate more actively and put forward more targeted suggestions and opinions.

4 Packaging design immersion experience experiment

4.1 Experimental design

To test the performance and user experience effect of this packaging design immersive experience system based on VR and semantic segmentation algorithms, and to verify the feasibility of the system to improve users' understanding and satisfaction of packaging design, and to improve users' participation in packaging design, an experimental study was conducted on this system. The study was conducted on 50 users with different professional backgrounds and different consumer experiences, and the users were mainly design undergraduates, general consumers, and consumers who had contacted or learned about the brand of this design. For the experimental factors, the variables were mainly categorised into independent and dependent variables. The independent variable is whether or not to utilise the immersive experience system based on VR + semantic segmentation algorithm packaging design, divided into experimental and control groups, the experimental group uses the immersive packaging design of VR + semantic segmentation algorithm, and the control group uses the flat two-dimensional display to complete the packaging design. The dependent variables are the degree of understanding of package design, satisfaction, participation, the length of time to complete the task, etc. The dependent variables are collected by interviews, users' behavioural data records, and interviews.

4.2 Experimental procedures

All the experiments were completed in a separate VR laboratory, which was equipped with highly configured computers, VR devices such as HTCVivePro2, and related accessories such as interactive handles to guarantee the stability and smoothness of the VR experience for the experimenters. All participants were divided into two groups, and the randomisation method was adopted to divide 50 participants into the experimental group and the control group, both containing 25 in the group. Before the experiment, the purpose, operation and precautions of the experiment were explained to the participants to ensure that they recognised the requirements of the experiment. For the experimental group: the subjects wore VR equipment and entered the immersive experience system of packaging design based on VR and semantic segmentation algorithms, observing the three-dimensional model of packaging in all directions, interacting with the packaging elements with their fingers, such as zooming in and out of the package, viewing the internal structure of the package, etc., and at the same time the semantic segmentation algorithms recognised and analysed the packaging elements to bring intelligent interactions for the subjects. For example, when the subject tries to open the text area on the package, the system will automatically play the content according to the text; when the subject tries to touch the material area of the package, the system will simulate the touch feeling of the corresponding material, and so on.

For the control group, participants viewed the two-dimensional flat picture of the package through the computer screen and could only observe the package from a fixed angle and could not interact with it. In the experience phase, both groups are required to complete the same experience tasks, such as the overall feeling of the package, pointing out the good and insufficient places in the package design, and giving advice for improvement. Record the behavioural data analysis of the experiencers during the experience process, such as experience operation time, operation frequency, and distribution of attention points. At the end of the activity on the two groups of people to carry out questionnaire research, the questionnaire content for the use of packaging design to understand how much, whether or not satisfied, whether or not willing to use, etc., the Likert scale –5 points were very dissatisfied to very satisfied, additional set of open questions to ask the experience of the concept of the packaging design of the experience of the views of the participants, to join the experience of the experience of the experience of the feeling of the use of some open questions and comments and suggestions. After the interview, some participants were interviewed to ask what they thought and felt during the research process.

4.3 Experimental results and analysis

The data statistics of the experimental results are as follows.

Table 2 Comparison of experimental results data between experimental group and control group

Assessment of indicators	*Experimental group*	*Control subjects*
Comprehension rating (average score)	4.2	3
Satisfaction rating (average)	4	2.8
Participation rating (average score)	4.1	2.5
Average time to complete tasks (minutes)	10	15

By analysing the data from the experimental results, the following bar graphs were plotted to better visualise the differences between the two sets of data. In terms of perception, the average score of the experimental group is 4.2, compared with the 3.0 of the control group, which shows that the immersive packaging design experience system based on VR and semantic segmentation algorithm allows users to understand the details and characteristics of the packaging design more thoroughly, and to learn about the constituent structure and materials of the packaging, as well as the information display of the packaging through personal observation and interaction. The average satisfaction scores of the experimental group and the control group are 4.0 and 2.8, indicating that the users in the immersive experience system have higher satisfaction with the packaging design experience, and the users are more interested in experiencing the interaction operation in the immersive packaging design, and they are more satisfied with the immersive experience and innovative interaction methods provided by the system. The average value of user experience degree in the experimental group is 4.1, which is significantly larger than that in the control group, which is 2.5. The result shows that the system formed by VR technology and semantic segmentation algorithm can effectively improve user participation, and the users are more active in exploring the relevant details of the packaging design, interacting with the packaging elements and putting forward their viewpoints in the process of experiencing the system.

From the point of view of the time to complete the task, the average time spent by users in the experimental group was 10 min, and the average time spent by users in the control group was 15 min this indicates that the immersive experience system helps to improve the efficiency of users in completing the task, and in the virtual environment, the users can get the information more easily by their way, and express the meaning of what they want to say, which saves time for them. From the in-depth interviews further analysis, we learned that the users highly evaluated the packaging design immersive experience system based on VR and semantic segmentation algorithms, and thought that the system was very novel and practical, which was conducive to users' better understanding of the packaging design as well as providing more effective opinions and suggestions for the improvement and innovation of the packaging design, and also pointed out that there were some suggestions for improvement of the system, such as further optimising the system's smoothness, increasing the number of It also points out that there are some suggestions for improvement, such as further optimising the smoothness of the system, adding more interactive methods and packaging design cases, and so on.

5 Application case analysis

5.1 Case selection

A case study of Red Bull's application of a VR-based semantic segmentation algorithm for packaging design immersive experience is selected as a case study. The beverage brand intends to develop a new beverage with new flavours to attract young people and increase the brand's advantage in the market. The traditional package design is limited to a two-dimensional planar presentation of product information, which lacks creativity and communication, so the design department of the beverage brand decided to design a new package design for an immersive experience based on VR semantic segmentation algorithm.

5.2 Case studies

The semantic segmentation algorithm analyses a large number of beverage packaging pictures and extracts the important information in the pictures, and specifically divides and identifies brand logos, flavour logos, product selling points, and so on. Then, based on the above information, 3D modelling technology is used to construct a 3D model of the packaged beverage and implant it into the VR scene. In the VR scene, the user can observe the packaged beverage in 360° through the handle and other tools, and rotate, zoom, and magnify it. The brand logo on the package can be clicked to pop up a window of brand introduction and brand development history; the flavour logo on the package can be clicked to pop up an introduction of the flavour of the packaged beverage and a description of the food ingredients; the selling point of the packaged beverage product can be clicked to pop up a window of introduction of the unique preparation process and function of the packaged beverage, which can be demonstrated in the form of animation. In order to verify the effect of VR and the semantic segmentation algorithm on this case, the data before and after the application are compared (Table 3). Before the application, consumers' feedback on the package design was collected through traditional market research, and the average consumer satisfaction with the package design was 3.5 points (out of 5), the average understanding of the product information was 3.2 points, and the degree of participation (mainly reflecting the enthusiasm of participating in the feedback on the package design) was low, only 20%.

After applying the package design immersive experience program based on VR and semantic segmentation algorithms, the data collected through the online VR experience platform showed that the average consumer satisfaction with the package design was 4.2 out of 5, the average understanding of the product information was 4.0 out of 5, and the degree of participation was higher at 60%, and the willingness to purchase was increased to 45% compared to the previous 30%.

Table 3 Comparison of data before and after application

Evaluation metric	*Before application*	*After application*
Satisfaction score (average)	3.5	4.2
Understanding score (average)	3.2	4
Engagement rate	20%	60%
Purchase intention	30%	45%

It can be seen that the application of VR and semantic segmentation algorithms makes consumers' satisfaction in packaging design, their understanding of product information, and their degree of participation gain significant improvement, which better stimulates consumers' willingness to buy and plays a positive role in brand marketing and product sales. This study presents an immersive packaging design system with several practical applications for real- world implementation. Designers and marketing teams can utilise it to develop interactive 3D environments that enable customers to examine packaging components, including material textures, structural configurations, and brand graphics, in an exceptionally intuitive way. This technology enables consumer-centred design validation via virtual showrooms, allowing customers to offer comments prior to the production of real prototypes, thus decreasing development costs and time. It can additionally provide customised packaging previews on e-commerce platforms, enhancing user engagement and buy intent. Furthermore, collaborative VR environments can improve cross-functional team conversations by enabling stakeholders to assess packaging concepts remotely and simultaneously. Nonetheless, despite these benefits, some constraints persist. The system's efficacy relies on the precision of the semantic segmentation algorithm, which can fluctuate based on package types and lighting circumstances.

Elevated hardware specifications for seamless VR rendering and restricted haptic feedback may potentially limit accessibility and realism. Moreover, the existing dataset may inadequately reflect the diversity of actual packing, highlighting the necessity for extensive data gathering and ongoing model enhancement in subsequent endeavours.

6 Conclusions

This study's findings indicate that the suggested immersive packaging design system, created by integrating VR technology and semantic segmentation algorithms, significantly improves user cognition, satisfaction, engagement, and work efficiency. In contrast to conventional two-dimensional display techniques, the immersive system offered a markedly more engaging and intuitive experience, allowing consumers to interact with packaging ideas within a dynamic three-dimensional setting. The experimental findings reveal that participants utilising the VR-based technology exhibited enhanced comprehension of packaging structure and components, reported more engagement, and accomplished assigned tasks more swiftly. Moreover, the application case study about a beverage brand confirmed the practical efficacy of the approach in actual marketing contexts. Users indicated an enhanced understanding of the packaging's informational content, heightened emotional connection with the product, and elevated buy intent. This indicates that the method improves both the visual and functional assessment of packaging while simultaneously reinforcing the 'consumer brand effect' and the 'product brand effect', therefore aiding brand communication and enhancing customer happiness.

This study presents an innovative, interdisciplinary methodology for packaging design, integrating sophisticated computer vision technologies with immersive virtual worlds to provide intelligent, user-centric design experiences. The technology facilitates real-time segmentation and interaction with packaging components, providing opportunities for individualised customisation, intelligent marketing, and consumer-oriented design enhancement. Future endeavours may concentrate on enhancing system responsiveness, broadening dataset diversity for more resilient segmentation, and incorporating multimodal feedback, including auditory and haptic interactions, to augment the immersive experience. The implementation of cloud-based collaborative VR platforms may enhance multi-user participation, enabling designers, marketers, and end-users to collectively engage in the package assessment process. These extensions would enhance the applicability of the proposed framework across domains, including e-commerce, retail innovation, and intelligent product visualisation. This study offers a progressive technique and technical framework for the creation of intelligent, interactive, and immersive packaging design solutions. It enhances the expanding research on digital media, human-computer interaction, and consumer experience, and offers a feasible avenue for the digital revolution of the packaging design sector.

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Declarations

All authors declare that they have no conflicts of interest.

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