Advancements in Three-Dimensional Virtual Try-On Technology

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Abstract. With the advent of the digital age and the widespread adoption of online shopping, 3D virtual fitting technology has emerged, fostering the integration of fashion and e-commerce and enhancing consumers' online shopping experiences. This paper reviews the development, key technologies, and applications of 3D virtual fitting technology across various domains. First, it explores the characteristics, advantages, and disadvantages of 3D human scanning technologies, including contact and non-contact measurement methods. It then elucidates the primary strategies for human body loading and clothing 3D modeling, encompassing traditional 3D visual modeling and deep learning methods. The paper outlines the critical applications and technical challenges in enhancing the realism and user experience of virtual fitting. Finally, it anticipates future trends in 3D virtual fitting technology, focusing on algorithm optimization, hardware advancements, and its role in promoting sustainable development.

Keywords: 3D Virtual Fitting, 3D Human Scanning, 3D Modeling, Deep Learning

1 Introduction

With the advent of the digital age, online shopping has become an integral part of daily consumption for many individuals[1]. However, when purchasing clothing online, consumers still harbor concerns regarding whether the attire will match their expectations. As computer graphics and computer vision technologies continue to advance and upgrade, they have not only enhanced consumers' online shopping experiences but also introduced a novel form of interaction[2]. Through the utilization of computer graphics and visual processing techniques, consumers can now engage in real-time virtual try-on experiences in a virtual environment, significantly enriching the experience of remote shopping[3].This innovation plays a pivotal role in meeting consumers' demands for convenient and personalized shopping experiences, while also providing retailers with opportunities to reduce costs and optimize inventory management by leveraging precise analysis and recommendation through user data acquisition[4,5].

E. P. H. Lau et al. (eds.), *Proceedings of the 2024 3rd International Conference on Information Economy, Data Modelling and Cloud Computing (ICIDC 2024)*, Advances in Computer Science Research 114,
https://doi.org/10.2991/978-94-6463-504-1_32

Virtual fitting technology originated from early 3D modeling in the 1990s and has gradually integrated into the e-commerce and fashion industries, evolving into a complex system[6]and is now widely applied across various consumer goods sectors such as apparel, jewelry, eyewear, and cosmetics. Some well-known brands have already introduced virtual try-on functionalities, enabling consumers to easily try on clothing or accessories via their smartphones or computers[7], thereby saving time and costs associated with queuing in physical store dressing rooms. However, virtual try-on technology still faces challenges, such as accurately capturing user body data, enhancing the realism of virtual try-on experiences, and integrating it with social media, e-commerce, and other technologies to further enhance user experience. Therefore, virtual try-on technology still possesses significant potential and room for development.

2 Research Progress of Three-Dimensional Virtual Try-On

In recent years, particularly influenced by the COVID-19 pandemic, an increasing number of consumers have turned to online shopping, bringing significant attention to virtual try-on technology. Virtual try-on systems allow consumers to virtually try on clothing items in the digital space before making purchase decisions, becoming a habitual activity for many consumers and enhancing their shopping experience[8]. Consumers can freely experiment, make decisions, and choose products according to their preferences[9]. At the same time, virtual fitting systems offer convenience to e-retailers and enhance sales efficiency[10].

The technologies involved in virtual try-on mainly fall into two categories: those based on two-dimensional methods and those based on three-dimensional methods. In the case of two-dimensional image virtual try-on, algorithms deform clothing images to align with reference body poses and ultimately showcase the try-on effect through image synthesis algorithms. Three-dimensional virtual try-on, on the other hand, involves first establishing a three-dimensional model of the clothing through software and then rendering it onto a three-dimensional body model to achieve the virtual try-on effect.

Research institutions and enterprises abroad have conducted extensive research and practical applications of three-dimensional virtual try-on technology, with processes ranging from data collection to design and production becoming increasingly mature[11]. Regarding three-dimensional body scanning, technologies in the United States primarily employ white light phase measurement methods, capable of scanning approximately 45,000 data points of the human body in just 10 seconds, with a scanning error of no more than 0.6 millimeters, ensuring precise measurements of body size. German technologies, on the other hand, can scan over 80,000 data points in 20 seconds, with measurement errors controlled to within 0.2 millimeters[12] . Furthermore, many foreign brands have begun to utilize three-dimensional virtual try-on technology for product design, such as V-Stitcher developed by Browzwea in the United States, Optitex developed and promoted by Optitex Ltd. in Israel, AGMS 3D by Asahi Kasei in Japan, and CLO3D by CLO Virtual Fashion in South Korea[13].

Numerous human body measurement databases have been established globally, particularly in Europe and the United States, where these databases are relatively large in scale and quantity. For instance, countries such as the United States, the Netherlands, and Italy have applied CASER human body measurement technology in multiple research fields. The 3D E-Commerce Center in the UK is actively exploring the commercial utilization of three-dimensional human body measurement data through the internet[14]. Li et al.[15]also developed a virtual fitting room system using the POVNet framework. This system generates high-quality images that faithfully represent the appearance of clothing items and allows users to mix and match various types of clothing, supporting body models of different skin tones, hair colors, and body types. Surveys have shown that using this system as a virtual fitting room for fashion e-commerce websites significantly increases user engagement.

3 Application of Three-Dimensional Virtual Try-On Technology

3.1 Application Scenarios of Three-Dimensional Virtual Try-On Technology

Currently, the application scenarios of virtual try-on technology mainly fall into three categories. The first category is consumer-oriented virtual try-on, which assists consumers in gaining a more intuitive understanding of the purchased clothing items and making personalized selections based on their preferences in terms of style, color, and other aspects. Wu et al.[16]developed a real-time interactive three-dimensional virtual try-on system utilizing Microsoft Kinect motion-sensing devices. By employing the OpenNI development library and multithreading techniques, they successfully constructed a motion capture module and a comprehensive virtual try-on platform. Hyunwoo et al.[17]created three-dimensional body models with various body shapes and sizes to study the impact of virtual try-on on online sales. The results indicated that the average sales per customer increased by 14,000 Korean won, and the return rate decreased by 27% with the use of virtual try-on. Marelli et al.[18]developed a framework-based virtual try-on experience for eyeglasses, reconstructing 3D faces from single images and allowing users to view the effects from multiple angles on computers or mobile devices, providing a high-quality virtual try-on experience.

The second category provides technical support for fashion designers and clothing manufacturers. By converting clothing designs into three-dimensional digital models, designers can create clothing styles more quickly and accurately, preview them in real-time before production, and avoid waste during the manufacturing process. Li et al.[19]applied modern computer-aided design (CAD) technology to the field of fashion design, directly drawing and modifying flat design drawings on computers using CAD to improve clothing design efficiency and reduce labor and resource time costs. Duan et al.[20]proposed a novel automatic three-dimensional scanning clothing try-on method, establishing correspondences between clothing and human bodies through feature matching and virtual sewing to obtain virtual try-on results. Moreover, it helps reduce environmental pollution and labor costs in the clothing manufacturing process. By utilizing virtual try-on technology, the number of pattern development and sampling iterations can be reduced, reducing the error rate in finished product manufacturing, saving time and costs. Gustafsson et al. [21] explored how suitability uncertainty affects the cost of online retail product returns, reducing retail supply chain costs associated with product returns by using virtual try-on. They found that virtual try-on could reduce up to 80% of return costs related to fit-related issues and regarded virtual try-on as an effective pre-sales try-on tool. It is evident that the application of three-dimensional virtual try-on technology will have profound impacts on the fashion industry and e-commerce sector, promoting the intelligence, digitization, and sustainable development of the clothing industry.

3.2 Main Technologies of Three-Dimensional Virtual Try-On

Three-dimensional virtual try-on combines techniques such as three-dimensional modeling, texture mapping, and physical simulation to digitally present real clothing models on computer screens. It automatically adjusts the size and style of clothing based on user body parameters to achieve a more tailored effect according to user needs. Compared to traditional two-dimensional virtual try-on, three-dimensional virtual try-on offers a more realistic and accurate fitting experience. Users can view the appearance of clothing from different angles and poses in a more intuitive manner, which is crucial for enhancing user satisfaction and purchase intention. Despite the drawbacks of high technical requirements, high costs, and poor compatibility, the future of three-dimensional virtual try-on still holds vast application prospects as technology advances and costs gradually decrease.

Specifically, the main technologies of three-dimensional virtual try-on include three-dimensional body scanning, three-dimensional body modeling, clothing three-dimensional modeling, and virtual three-dimensional try-on. As show in figure 1.

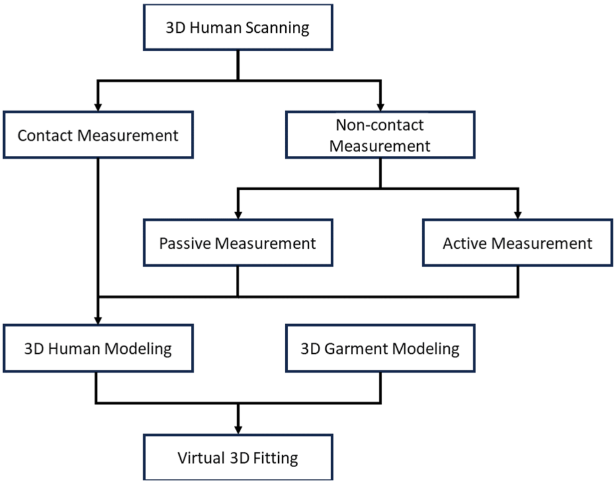

Fig. 1. Flowchart of Virtual Three-Dimensional Try-On

2.2.1 Three-Dimensional Body Scanning

Three-dimensional body scanning mainly involves contact and non-contact measurements[22].Contact measurement refers to the method where measurement personnel directly contact the body during the measurement process, either through traditional manual measurements or measurement instruments. Contact measurement offers advantages such as speed and intuitiveness but suffers from drawbacks such as time-consuming procedures and low accuracy[23].

The mainstream approach nowadays is non-contact measurement, which includes passive and active methods. Passive measurement typically captures or scans body surface images or data for measurement. It offers high accuracy, simple operation, and no direct contact with the subject. However, it requires sufficient light or signals for effective measurement. Common techniques in passive measurement include stereo vision and multi-view imaging. Active measurement involves projecting light onto the object using measurement devices, capturing images with CCD cameras, and generating point cloud images through coordinate transformation and stitching. Dimension data is then obtained through point cloud preprocessing and algorithm calculation[24]. Active measurement includes techniques such as laser triangulation, structured light measurement, Moire fringe interferometry, and white light phase measurement, offering advantages such as high accuracy, strong reliability, fast speed, and wide applicability. As show in table 1.

Table 1. Comparison of Human Body 3D Scanning Methods

Scanning Method	Type	Cost	Measurement Time	Accuracy	Interference Resistance	Ambient Light Requirement	Data Processing Difficulty
Contact Measurement	Direct	Low	Short	Low	Strong	Normal	Easy
Stereoscopic Vision Method	Passive	Low	Long	High	Weak	Normal	Difficult
Multi-view Imaging Method	Passive	High	Short	High	Moderate	Normal	Difficult
Laser Triangulation Method	Active	Medium	Short	High	Strong	Normal	Easy
Structured Light Method	Active	Medium	Short	High	Weak	Dark	Moderate
Moiré Fringe Interference Method	Active	Low	Short	High	Weak	Dark	Moderate
White Light Phase Method	Active	Medium	Short	High	Moderate	Normal	Difficult

Currently, the most commonly used device is the Kinect three-dimensional body scanning device developed by Microsoft[25], which is widely applied in fields such as computer vision, virtual reality, and augmented reality. Kinect utilizes a combination of infrared depth sensors, RGB color cameras, and depth sensors[26]to dynamically capture user movements, postures, and environmental information, enabling three-dimensional body scanning. Landau et al.[27]proposed a high-fidelity Kinect infrared and depth image predictor and simulator, which accurately reproduces significant images by simulating the physical properties of the emission and reception systems, unique infrared dot patterns, and disparity/depth processing techniques. This model is used to provide real ground data sets for any object and scene and is accompanied by CAD models. Chhokra et al.[28]introduced a new RGB-DI database containing videos of 108 subjects captured using Kinect sensors. This database facilitates research on face recognition algorithms using unimodal and multimodal information. Wan et al.[29]utilized Kinect combined with three-dimensional body scanning, reconstruction, and measurement techniques to propose a more convenient and secure body composition analysis system, which rapidly obtains real three-dimensional data based on scanning results. Krzeszowski et al.[30]developed a body measurement parameter estimation system based on complete body three-dimensional scanning using Kinect v2 sensor cameras. This system is simple, time-efficient, does not require expensive measurement tools or professional training personnel, and provides highly accurate parameter estimates. Eichler et al.[31]implemented and evaluated a multi-camera spatiotemporal calibration method using multiple Azure Kinect devices, which can be widely used for three-dimensional tracking of human poses and movements without specialized equipment. Additionally, instruments such as Vitus Smart, Cyberware Wb4, and 3DLS utilizing laser triangulation, as well as instruments utilizing white light phase methods like $[TC]^2$ and CubiCam based on Moire fringe interferometry principles, are also available. As show in figure 2.

Fig. 2. Kinect 3D Human Scanning Device

2.2.2 Three-Dimensional Human Body Modeling

After obtaining three-dimensional point cloud data from scanning, further processing and modeling of the information are required. The modeling method of three-dimensional body scanning technology involves directly scanning the human body using scanning equipment to acquire point cloud data, which is then processed to create a three-dimensional model of the human body. This method offers advantages such as speed and high accuracy, resulting in higher fidelity models. However, it also presents challenges such as lengthy post-processing and complex algorithms.

The primary methods for modeling include surface modeling, solid modeling, and physical modeling, with surface modeling further divided into triangulated surface modeling and parametric surface modeling[32]. Triangulated surface modeling divides the human body surface into numerous small triangular facets to represent and reconstruct the geometric shape of the body. This method processes and analyzes the input point cloud data using computer vision and graphics techniques to extract key features such as body part positions and poses. These features are used to construct a network of triangular facets representing the body surface, which are interconnected to form a continuous mesh approximating the body's geometry. The more triangular facets, the higher the accuracy and detail of the human body model. For instance, Chi et al.[33]proposed a novel three-dimensional human body modeling method based on key point labels and body part segmentation, achieving personalized customization of three-dimensional human body models through precise measurement of body data and feature extraction based on expert knowledge, with significant advantages in accuracy and visual quality.

Parametric surface modeling describes and reconstructs the shape of the human body using mathematical surface equations. In this method, the body's surface is represented as parameterized surfaces, typically using parameter coordinates to describe points on the surface. Common parametric surface modeling methods include Bezier surfaces, B-spline surfaces, and Non-Uniform Rational B-spline (NURBS) surfaces. These methods control the shape of the surface by adjusting the positions and weights of control points, enabling precise control and adjustment of the human body shape. For example, Zhakatayev et al.[34]used triangular splines instead of traditional B-splines to discretize generalized coordinates and velocities, derived useful identities for triangular spline functions, and proposed a simple framework for synthesizing human motion for inexperienced users to start their research on human motion simulation and optimization of human motion trajectories.

2.2.3 Clothing Three-Dimensional Modeling

Currently, the mainstream methods for clothing three-dimensional modeling involve traditional 3D visual modeling and deep learning[35].

Traditional 3D visual modeling primarily utilizes Structure from Motion (SFM) technology to assist in clothing three-dimensional modeling[36]. Specifically, when using SFM for clothing modeling, multiple images from different angles need to be captured, and computer algorithms are used to match and register these images. Through registration, parameters such as camera position, orientation, and intrinsic parameters corresponding to each image can be determined. Then, using this parameter information and the spatial relationships between matching points, the shape and position of the human body or clothing in the three-dimensional scene can be reconstructed. This technology can improve modeling efficiency and accuracy and help designers better understand and present their creative ideas. However, it also has some drawbacks, such as sensitivity to lighting and textures, the need to capture multiple photos from different viewpoints to obtain sufficient information to construct a 3D model, and potential failure if the objects in the scene lack adequate lighting or textures to distinguish. Additionally, this technology requires the use of complex algorithms and tools, resulting in high time and computational complexity, which increases the threshold for using this technology. Özyeşil et al.[37]mainly investigated recent developments in camera motion estimation and the use of estimated motion and features to recover 3D structures, introducing the latest methods for camera position estimation in the literature, and then discussing 3D structure recovery techniques.

Deep learning methods utilize artificial intelligence technology, and by leveraging deep neural networks, they can automatically learn the structural and stylistic features of clothing from a large amount of data, thereby generating high-quality three-dimensional clothing models. Deep learning methods are particularly suitable for handling tasks of clothing modeling with high style diversity and complexity, enabling creative and personalized design simulations while maintaining high efficiency. An important advantage of deep learning methods is their ability to handle data. Without relying on single images or fixed viewpoints, this method can comprehensively utilize a large amount of data resources containing information on different material properties, lighting conditions, and diversified design styles, thereby improving the adaptability and accuracy of the model[38]. Additionally, with the rapid development of computer vision and machine learning technologies, deep learning methods have also significantly improved in terms of time and computational efficiency. Bhatnagar et al.[39], by training the MGN model, can predict the shape of the human body and the geometric shape of clothing from a small number of video frames, using deep learning models to achieve the association and transfer of clothing with human body shape and posture. Lee et al.[40]proposed a new method called Double Reverse Diffusion (DReD), which uses deep learning technology to reconstruct realistic clothing details from images and human body information, improving the accuracy and realism of clothing modeling.

2.2.4 Virtual Three-Dimensional Clothing Try-On

Upon completing the three-dimensional scanning of the human body and the three-dimensional modeling of clothing, it is necessary to match the body parts of the human body model with the clothing model to ensure that the clothing fits perfectly with the body. This is achieved through the use of algorithms and computer vision techniques to establish the correspondence between the human body and the clothing. This can be done by matching the landmarks of the human body with those of the clothing, finding the corresponding relationships. Techniques such as shape matching, point cloud alignment, and joint angle calculation can be used to establish these relationships. After establishing the initial correspondence between the human body and the clothing, further adjustments and adaptations are needed to ensure accurate alignment. This may involve scaling, rotating, or deforming the clothing model to better fit the shape and posture of the human body model. Once an accurate correspondence between the human body and the clothing is established, users can engage in real-time interaction in virtual fitting applications. They can change the posture, rotation, or movement of the human body, and the clothing will accordingly follow and maintain its correspondence with the human body. Users can observe the appearance and fit of the clothing from different angles and postures.

Zunair et al.[41]proposed a Fabric-Informed Fitting Adjustment (FIFA) model, which adapts the overall structure of clothing by filling fabric, and then refines and deforms

the target clothing through training virtual try-on pipelines. This approach has significantly improved synthetic try-on images, preserving not only the logos, textures, and embroideries of the clothing but also better handling complex postures.
Kuribayashi et al.[42]developed an image-based virtual try-on system capable of adjusting clothing sizes. By analyzing the proportions of the human body to the clothing, they utilized the key point coordinates recognized by OpenPose to adjust the details of the collar and overlapping areas when the clothing size changes, thereby optimizing the visual effects of virtual try-on.

4 Conclusion

This paper reviews the development and technical implementation of three-dimensional virtual try-on technology, as well as its applications in different fields. Key technologies such as human body 3D scanning, modeling, and garment 3D modeling are discussed. Despite significant progress in enhancing the online shopping experience and optimizing retail strategies, 3D virtual try-on technology still faces challenges in terms of technical accuracy, cost, and widespread adoption. The future development trends of this technology are expected to focus on several aspects: firstly, algorithm optimization, as advances in deep learning and artificial intelligence will further improve the accuracy and realism of 3D virtual try-on. Secondly, hardware improvements, as the increased accuracy and reduced costs of sensors and scanning devices will make 3D scanning technology more accessible to individual users and retailers. Thirdly, in terms of cross-domain integration, 3D virtual try-on will integrate with social media, augmented reality (AR), and virtual reality (VR) technologies, providing a more immersive and personalized shopping experience. Lastly, the development of 3D virtual try-on technology will drive the transformation of fashion design and retail environments towards sustainability, for example, by reducing the production of physical samples, thereby reducing production surplus and waste. In conclusion, with technological advancements and cost management, 3D virtual try-on technology will continue to expand its applications in the fashion and retail industries, creating greater value for consumers and businesses, and leading to a more sustainable, efficient, and consumer-centric shopping future.

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