Research Progress of Virtual Reality Modeling Based on Three-Dimensional Reconstruction Technology

Wei Long†, Tianyu Wang†, Yujie Lu, Xu Huang, Qiang Gao, Linhua Jiang*
Zhejiang Province Key Laboratory of Smart Management & Application of Modern Agricultural Resources, School of Information Engineering, Huzhou University, Huzhou, Zhejiang, China

*Corresponding author’s email: 11594@zjhu.edu.cn
†Co-first author

Abstract. The limitations of virtual reality (VR) modeling and construction is one of the key issues in the recent research. An accurate model constructed based on real-world scenes is time and resource consuming. The three-dimensional (3D) reconstruction technology can efficiently construct models based on real-world objects, which is ideal for high-speed VR modeling system. This paper introduces the modeling examples based on 3D reconstruction in VR devices, compares the advantages/disadvantages between various reconstruction methods and comprehensively introduces the combination of the different methods. The summary and future development trend is also discussed at the end.

Keywords: virtual reality; three-dimensional reconstruction; modeling; non-contact measurement

1. Introduction
Virtual reality (VR) is a widely-used simulation technology to generate a virtual digital environment based on computer science and devices. VR devices can create a 3D spatial environment and provide an immersive experience to the users. Modeling is a significant part of VR research that determines the truthiness and immersion degree of VR scenes. In the traditional research procedure, the object model in the VR scene is pre-designed and implemented manually, which is slow and tedious. However, a growing number of applications, especially in design, architecture and other industries, put forward an increasing demand for 3D reconstruction from the real world. Therefore, reconstructing a high-quality model for the real-world object in a straightforward and fast way based on virtual reality has become an urgent research topic.

2. Research progress of three-dimensional reconstruction technology
Three-dimensional reconstruction refers to the process of obtaining surface information of an object by using three-dimensional measurement technology and building a model. Three-dimensional reconstruction method can be simply divided into contact type and non-contact type according to whether the measuring tool touches the surface of the measured object [1]. The contact type measures
the three-dimensional information of the surface of the object by contacting the probe with the surface
of the object to be measured. The contact type is the most intuitive and easy to implement three-
dimensional measurement method. Usually a coordinate measuring machine is used as a measuring tool,
and the probe moves on three vertical tracks, when it touches the surface of the object, the surface
coordinates of the object are calculated according to the reference point of the measuring machine. The
accuracy of the contact measurement is high and can reach the nanometer level, but the contact
measurement is easy to scratch the surface of the measured object, and cannot be applied to the
measurement of large objects and large-scale scenes. It is not suitable for the actual 3D reconstruction.
application Non-contact measurement can be divided into active measurement and passive
measurement. Passive measurement method does not need to add additional light sources.
Under natural light, multiple cameras are used to shoot multiple images of the measured object from different
viewpoints. After processing the image, color information and the depth of the object is obtained using
computer vision technology. Active measurement methods need to use additional auxiliary light sources
to project objects. Common methods include laser ranging and structured light measurement. The laser
ranging method is also called time-of-flight, in which the emitter emits laser to the measured object at
regular intervals, the detector receives the reflected light. Since the propagation speed of light is
constant the depth of the measured object is obtained according to the flight time of the ray. The time-
of-flight method is simple in principle, fast in measurement, can realize real-time measurement. It is
widely used in depth sensors, such as the second-generation Kinect camera. In structured light
measurement, the emitter emits point, line and area light sources to the object surface, and another
camera observes the position of the light spot, then the depth of the object surface is calculated by
triangulation method [2]. The data obtained by different measurement methods are processed and
calculated to complete 3D reconstruction. The measurement method that uses the triangulation method
to calculate is simple, small in calculation, low in cost, but it has the problem of occlusion and is greatly
affected by light.

3. Three-dimensional reconstruction principle
The main steps of laser ranging method include point cloud data acquisition, point cloud data
preprocessing and 3D reconstruction. Figure 1 shows how the 3D laser scanner can scan the measured
object to obtain the original point cloud data [3]. However, due to the complex structure of the surface
of the measured object, the original point cloud data is huge, and the storage and transmission of these
data will consume a large number of computer resources, so the point cloud data need to be
compressed and preprocessed. When using the compressed point cloud data, only the compressed files
need to be decoded. At present, the commonly used compression methods are normal distribution
transform (NDT) [4] and Octomap [5]. If 3D reconstruction is directly performed on the huge
point cloud data, the efficiency will be very low. It is necessary to streamline the point cloud data,
remove redundant data and optimize the distribution density of the point cloud. The simplified point
cloud data forms a triangular mesh, which is mapped on the surface to complete the model construction
[6].

![Figure 1. Schematic diagram of laser ranging method](image-url)
In Figure 2, the projector projects structural light to the measured object, and another camera captures the image generated by structural light on the surface of the measured object [7]. According to different shapes, structured light can be divided into point structured light, line structured light and surface structured light [8]. The point structured light method projects the point light source onto the surface of the object, the camera obtains the image of the light point, but each image can only obtain the three-dimensional information of one point, the information obtained is small, and the measurement speed is slow. In practical applications, line structured light and surface structured light are often used for measurement. The linear structured light strikes the surface of the object to form a light bar, which will deform when moving on the surface of the object. The camera records the deformation and adjusts the deformation to calculate the three-dimensional information of the object to be measured [9]. The multi-line structured light is modulated by adding a grating to the light source, and a lot of light bars are formed on the object, these light bars contain a lot of information. The measurement method of surface structured light first should calibrate the system to obtain calibration information, encode and project structured light, and decode the image projected on the surface of the object to obtain three-dimensional data [10]. The surface structured light method does not require multiple scans, and the sampling is convenient to quickly obtain the three-dimensional information of the object surface, but the accuracy is not as good as the point and line structured light.

![Figure 2. Schematic diagram of point structured light method](image)

Passive measurement method uses one or more cameras to collect images of the object to be measured, and the processing process generally includes camera parameter calibration, feature extraction and three-dimensional model reconstruction [11]. The calibration of camera parameters is to determine the relationship between the geometric position of an object in space and the corresponding point in the image, and to establish a geometric model. The main calibration methods include Zhang's plane calibration method and camera self-calibration method. The self-calibration method is based on the data obtained by its own sensor, which is simple and flexible. Zhang's plane calibration method simplifies the traditional calibration method, replacing the three-dimensional calibration board with a plane calibration board, which reduces the difficulty of calibration and has higher accuracy than the self-calibration method. According to the number of cameras used, it can be divided into monocular vision method, binocular vision method and trinocular vision method. Monocular vision methods generally include two reconstruction methods. The first one takes a single or multiple images from the same viewpoint, and calculates the depth of the measured object through the texture, contour, brightness and other information contained in the images [12]. The second method is to shoot images from multiple viewpoints, compare the same features of images from different viewpoints, and calculate the 3D information of the measured object by matching constraints. The principle of binocular vision method is similar to that of human eyes to recognize objects. As shown in Figure 3, two cameras shoot at different viewpoints, acquire images of the same object from different perspectives, and convert disparity information of different images into depth data. In the trinocular vision method, an extra camera is added on the basis of double cameras, which provides more constraints [13] and solves the problems of blurred edges in binocular vision method.
Figure 3. Schematic diagram of binocular vision method

4. Application in virtual reality
The combination of virtual reality technology and 3D reconstruction has been applied in many fields, such as ancient architecture restoration, landscape design, complex terrain reproduction, etc., especially in the construction of large-scale scenes and dangerous scenes.

Due to environmental and human factors, ancient buildings generally at risk of damage, so the restoration, protection and reappearance of ancient buildings has become an important research topic. The combination of 3D reconstruction technology and virtual reality technology provides a new idea for this research topic. Some scholars use laser scanning to collect the images of ancient buildings, and after denoising the images, they use VR technology to render the outline and texture, and complete the restoration and reproduction of ancient buildings [14]. In another study, data were obtained by laser scanner, and ancient buildings were reproduced [15]. Three-dimensional reconstruction technology is also applied to digitization of cultural relics, virtual display and so on [16,17].

Large-scale landscape design is difficult to be completed by traditional manual modeling. On the one hand, it is difficult to obtain data, on the other hand, modeling workload is huge. Three-dimensional reconstruction technology has the ability of automatic construction, which can easily complete the construction. For example, in the design of rural landscape, drones capture high-resolution images, generate grids and textures through image acquisition of point clouds, and build models [18]. In landscape design, ordinary 2D and 3D display methods can't well perceive information such as terrain fluctuation and transparency. The combination of 3D reconstruction technology and virtual reality technology provides users with virtual scenes and a completely immersive experience based on real landscape environment [19].

The complex scenes here refer to dangerous scenes and fragile ecological landscapes. The mine production system is complex, facing the danger of gas explosion and collapse. The application of virtual reality technology in mine reconstruction provides convenience for mine survey, technical training and safety education [20,21]. China has a large number of caves, laser scanning technology is used to digitally reconstruct caves to strengthen the management and protection of caves [22]. Some remote island reefs which are not suitable for living and managing for a long time use virtual reality technology to realize remote monitoring and management [23].

5. Comparison of three-dimensional reconstruction methods
The advantages of the time-of-flight method include simple measurement principle, easy operation, without too many parameters adjustment, and efficient acquisition of large amounts of data, it can meet real-time measurement, and the measurement system is stable and reliable [24]. The ranging accuracy is relatively high, the measuring range is large, the maximum measuring distance exceeds 100m. For example, the Focus3D laser scanner of FARO Company has the longest detection distance of 120m and the visual range of 153m. The range error at 10m and 25m is ± 2mm. The disadvantage is that the measurement accuracy will be affected by the measurement distance and imaging environment along
with the measurement distance. Because of the stability of its system, it is often used in scene construction and distance sensing. At present, it has been widely used in the fields of unmanned aerial vehicles and unmanned vehicles. For example, the products of Velodyne Lidar Company are used for time-of-flight ranging in unmanned vehicles.

Structured light measurement adopts direct triangulation measurement method, the measurement equipment is low in cost, small in size, easy to install and carry, and high in measurement accuracy. However, it is necessary to calibrate the parameters of projector and camera [25], and the calibration errors of these parameters have great influence on the calculation of point cloud. The effective measuring range is small, and it also has certain requirements for environmental light. Since the wavelength of structured light is within the wavelength range of visible light, it is easily affected by ambient light, and the intensity of structured light decreases with the distance, so the measurement accuracy is easily affected. The measuring range of point structured light is about 1m, and the precision can reach less than 1mm. The laser scanning measurement system based on point acquisition developed by Xi has an accuracy of ±10µm [26], error is less than 0.375%. It takes a long time to scan horizontally and vertically to get the information of the whole object surface. Line structured light measurement only needs to scan along one direction, which shortens the time of data acquisition. The extraction of the center line of laser band seriously affects the measurement accuracy [27]. Cui Xi’an adopted an adaptive iterative algorithm based on the barycenter method to obtain the center of the laser scalpel, with an accuracy of 10µm [28]. In Zhang Jia, the center of light bar is calculated by the quadratic weighted gray gravity center method with adaptive width, and the variance between the measured result and the center line is 0.1pixel [29]. Surface structured light measurement only needs to scan once, which greatly improves the measurement speed and is suitable for the reconstruction of small objects. Wang proposed a piecewise quantization phase encoding method, which embeds the quantized codeword into the phase, the measurement accuracy is improved, and the error is 0.051mm [30]. Liu adopts the codec method based on absolute phase to realize the measurement of absolute phase, and the precision of the measurement system reaches 0.11mm [31].

The monocular vision method only needs one camera to shoot, which is not only fast in measurement and reconstruction but also low in cost, usually the reconstruction accuracy is not high, and it is necessary to obtain a large amount of measured object information to improve the accuracy. The binocular vision method is mature, which can realize the measurement and reconstruction of large-scale scenes with high accuracy. However, the camera needs to be calibrated, and the calculation is too large to be applied to real-time measurement. Based on binocular vision technology, Shi Weicheng used contour edge line fitting algorithm to reconstruct the workpiece, the error of the reconstructed model is ±0.5mm [32]. The accuracy of the long-distance target ranging algorithm based on binocular vision proposed by Chen was 0.766cm. Compared with binocular vision method, the multi-vision method has higher measurement accuracy and better effect on large scenes and small objects. The disadvantages are that the measurement method is complex, difficult to control, and the amount of calculation is high. Soheilian used the multi-vision method to reconstruct the city streets, with an average accuracy of 3.5cm [33]. According to Zhao Xinyang’s method of tracking and positioning surgical instruments based on multi-eye vision, the errors of dynamic positioning and static positioning are both less than 0.15mm [34].

| Method                      | Reconstruction effect                  | Measuring speed                  | Applicable scenarios         |
|-----------------------------|---------------------------------------|----------------------------------|-------------------------------|
| Time of flight method       | High precision and average reconstruction effect | Fast measurement speed and high cost | Large scene                  |
| Point structured light method | High precision and good reconstruction effect | The measurement is difficult and slow, and it is easily affected by | Objects of smaller size      |

Table 1. Comparison of various reconstruction methods
surrounding light sources

| Method                        | Measurement Characteristics                                                                 | Objects                              |
|-------------------------------|------------------------------------------------------------------------------------------------|--------------------------------------|
| Line structured light method  | High precision and good reconstruction effect                                                   | Objects of smaller size              |
| Surface structured light method| High precision and good reconstruction effect                                                   | Objects of smaller size              |
| Monocular vision method       | Low precision and poor reconstruction effect                                                    | Objects of smaller size              |
| Multi-vision method           | High precision and good reconstruction effect                                                   | It has a wide range of applications and can measure most scenes |

It can be seen from the table that the time-of-flight method is simple in measuring mode, fast in measuring speed and wide in measuring range, and can achieve good accuracy. Compared with the structured light method, although the accuracy of the time-of-flight method is slightly reduced, it reaches the level of application, and has obvious advantages in large-scale measurement. It is very suitable for building large-scale scene models, such as buildings and terrain models, and is widely used in practice. Point structured light method needs to be scanned point by point, line structured light needs to be scanned line by line, so the measurement speed is slow. The scanning speed of planar structured light is the fastest, but it needs encoding and decoding, the measurement method is also complex. All they are greatly influenced by ambient light, and they are all suitable for measuring small objects with high accuracy. In practical applications, plane structured light method and line structured light method are mostly used, the research on structured light mostly focuses on the coding mode of structured light. Compared with other methods, the visual method has the outstanding advantage that it can obtain the color information of the object surface, which is conducive to constructing a more realistic model. Monocular vision method, a rapid and simple measurement method, the reconstruction accuracy is low, often can’t meet the practical application to requirement. The multi-eye vision method has a good reconstruction effect and a wide range of applications. However, the camera needs to be calibrated, the measurement method is complex, measurement speed is slow, the cost is expensive, it is rarely used in practical application. The method in this paper basically meets the requirements of different precision and range, and can realize the reconstruction of various scenes.

6. Summary
With the gradual maturity of 3D reconstruction and the development of virtual reality, the requirement of combining the two technologies become an urgent commercial demand. This paper introduces the application of 3D reconstruction technology in virtual reality, enumerates the modeling examples of 3D reconstruction algorithms, explains the advantages, disadvantages and application scenarios of various 3D reconstruction technologies. The 3D reconstruction technology improves the efficiency of modeling, broadens the application range of modeling, and helps to enhance the immersion of virtual reality.

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