

Acquisition method of asphalt pavement texture information based on the CPR Technology

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Abstract. In order to obtain the asphalt pavement texture information in real time and accurately monitor the anti-skid performance of the road pavement, an automatic close range photogrammetry system (ACPR system) was proposed and built based on the circle arranged three cameras close range photogrammetry (CPR) technology to obtain the asphalt pavement surface texture. Automatic image acquisition and 3D reconstruction were achieved by the ACPR system. Sand patch method and laser scanning method (ZGScan) were used to collect the on-site comparison test of the asphalt pavement texture. Mean texture depth (MTD) and root mean square roughness (RSMR) were chosen as the statistical indicators of road surface texture. The results show that the texture data obtained by ACPR system has relatively high accuracy and efficiency, and the recognition accuracy is close to 0.02mm. The ACPR system improves the efficiency and accuracy of traditional close range photogrammetry and provides real-time and effective road surface anti-skid information for subsequent safety braking of autonomous vehicle.

Key words: Anti-skid performance; automated close range photogrammetry system; asphalt pavement texture information; mean texture depth (MTD); root mean square roughness (RMSR)

1 Introduction

In recent years, numerous highway traffic accidents happened due to the lack of asphalt pavement anti-skid performance. It is known that good pavement anti-skid performance can provide high-speed vehicles with sufficient friction to ensure the safety and comfort of the vehicle during driving. Anti-skid performance of asphalt pavement relates to road surface texture directly, especially on rainy days, reasonable asphalt pavement texture can better discharge water, penetrate the water film, thereby reducing the traffic accidents due to water drift slipping. Therefore, it is of great significance to periodically monitor the surface texture of asphalt pavement during the whole life cycle and obtain the anti-skid performance of asphalt pavement in time [1, 2].

The earliest method of obtaining the surface texture of asphalt pavement is the contact measurement [3], which indirectly evaluates the surface texture of pavement by reading relevant index of instrument or calculating the texture depth and coefficient of friction. During the test, the traffic in the measurement site is affected, and the detailed information about the

macroscopic texture and microscopic texture of the asphalt pavement is not available. Based on the above research, the non-contact measurement has been explored and researched by scholar world widely. Non-contact measurement mainly includes digital gray image [4], industrial CT scanning [5, 6], laser measurement, close range photogrammetry. These methods are involved in digital reconstruction of the road surface texture three-dimensional model. Compared with other non-contact measurement methods, the close range photogrammetry (CRP) method has the advantages of reducing test time and improving measurement efficiency [7, 8]. In order to have sufficient overlap between the captured images, the traditional close range photogrammetry needs to capture more than 6 pictures around the object to be measured [9]. The number of image acquisition greatly affects the measurement efficiency, especially the processing time of post-image and operation time of three-dimensional modeling [10]. In order to improve the efficiency of obtaining the surface texture of asphalt pavement by the method of CRP, some scholars use the close range photogrammetry method based on dual camera to collect the surface texture of asphalt mixture specimen [7]. Although the

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mentioned method can improve the measurement efficiency, loss of texture information is unavoidable. Therefore, it is urgent to improve the traditional close range photogrammetry technology, and improve the precision and efficiency of texture reconstruction while guaranteeing the integrality of texture information.

Based on this, this paper proposes a close range photogrammetry method based on circle arranged three cameras. The ACRP system realizes the texture image collection and three-dimensional model reconstruction of asphalt pavement surface. MATLAB and Python are used to create three-dimensional reconstruction software module, which controls the CRP platform illumination and image acquisition process, and performs calculation of digital information and related texture parameters of surface texture of asphalt pavement. The ACPR system is used to test the texture information of asphalt pavement in site, and the surface texture parameters obtained by laser scanning method (ZGScan) and sand patch method are compared with those of ACRP system.

2 ACRP system

The close range photogrammetry can be divided into three major processes, including close range photography, image processing and 3D reconstruction [10]. After the image acquisition, a series of processing and operation of the image is needed to complete the three-dimensional reconstruction.

2.1 Basics of close range photogrammetry

Close range photogrammetry is based on binocular stereo vision technology which obtains images with time series of the same target at different points of time or different positions. By analyzing the geometric constraints of the image sequence, the three-dimensional coordinate information of target surface can be calculated. The principle is shown in Figure 1.

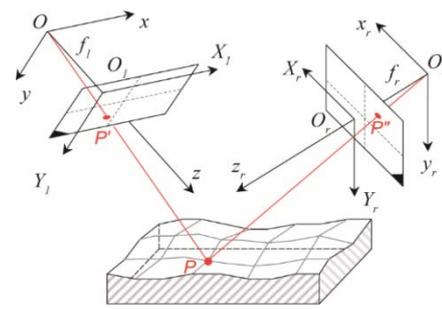


Fig. 1. Fundamentals of close range photogrammetry

Assume the camera is located at the origin of the world coordinate system $O-xyz$ at the initial moment, the captured image is in the coordinate system $O_1-X_1Y_1$, and the effective focal length of the camera is f_1 . The camera coordinate system is $O_r-x_r y_r z_r$ at moment 2, the image coordinate system is $O_r-X_r Y_r$, the effective focal length is f_r . According to camera perspective transformation model, the formula can be obtained, as shown below:

$$s_1 \begin{bmatrix} X_1 \\ Y_1 \\ 1 \end{bmatrix} = \begin{bmatrix} f_1 & 0 & 0 \\ 0 & f_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (1)$$

$$s_r \begin{bmatrix} X_r \\ Y_r \\ 1 \end{bmatrix} = \begin{bmatrix} f_r & 0 & 0 \\ 0 & f_r & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} \quad (2)$$

Where, the relationship between the coordinate system $O-xyz$ and the coordinate system $O_r-x_r y_r z_r$ is transformed by the spatial matrix M_{1r} , ρ_r is the coordinates of the target space point P (see Figure 1) on the image of the subsequent time series. Therefore, the mathematical model of three-dimensional coordinates of target space point is established:

$$\begin{aligned} x &= zX_1 / f_1 \\ y &= zY_1 / f_1 \\ z &= \frac{f_1(f_r t_x - X_r t_z)}{X_r(r_7 X_1 + r_8 Y_1 + f_1 r_9) - f_r(r_1 X_1 + r_2 Y_1 + f_1 r_3)} \\ &= \frac{f_1(f_r t_y - Y_r t_z)}{Y_r(r_7 X_1 + r_8 Y_1 + f_1 r_9) - f_r(r_4 X_1 + r_5 Y_1 + f_1 r_6)} \end{aligned} \quad (3)$$

The focal length f_1, f_r , coordinates P' and P'' of the target space point P on images have been known, inputting R which is the rotation matrix of every two camera positions and the translation vector T , then the three-dimensional space coordinates of the target point P can be calculated.

2.2 Establishment of ACRP system

In order to improve the efficiency of traditional close range photogrammetry, this paper builds an ACRP system, which includes close range photogrammetry platform and three-dimensional reconstruction software module.

2.2.1 Close range photographic platform

The close range photographic platform comprises three Basler industrial cameras and a circular 60LED shadowless lamp illumination module, which are connected with the master computer via the USB3.0 data cable. Then use the camera API program on the master computer to send the command, which controls shadowless lamp module to provide illumination, and trigger three cameras to complete the acquisition of images at the same time, which can collect three images each time [11]. Camera parameters are shown in Table 1.

Table 1 Camera parameter settings

Specifications	Properties	Specifications	Properties
Camera model	Basler acA1300	Frame Rate	60 FPS
Sensor type	PYTHON 5000	Lense model	Basler Lens
	CMOS		C125
Effective pixels	500×10^4	Focal length	8.0 mm
Shutter	Global Shutter	Aperture	F1.8-F22.0
Shutter speed	1/4,000 s		

Note: CMOS: Complementary Metal Oxide Semiconductor. CMOS technology is used for several analog circuits such as image sensors.

The size of the close range photographic platform is $1 \times 1 \times 0.5\text{m}$ ($L \times W \times H$), the three cameras on the platform are arranged in a circular trajectory of 0.5m radius with 120° interval. The shadowless lamp illumination system is installed at the center of the circle, the shadowless lamp power is 60W, the brightness adjustment range is 0~4000LX, The detailed structure and equipment of the ACRP System platform are shown in Figure 2.



Fig. 2. Structure of ACRP System platform

2.2.2 3D reconstruction software module

Through MATLAB and Python mixed programming to complete the three-dimensional reconstruction software module, the function of the module includes control of the CRP platform lighting and image acquisition. Meanwhile, complete the subsequent image processing and three-dimensional reconstruction to obtain the asphalt pavement surface texture digitization information and related texture parameters. Three-dimensional reconstruction module interface is shown in Figure 3.

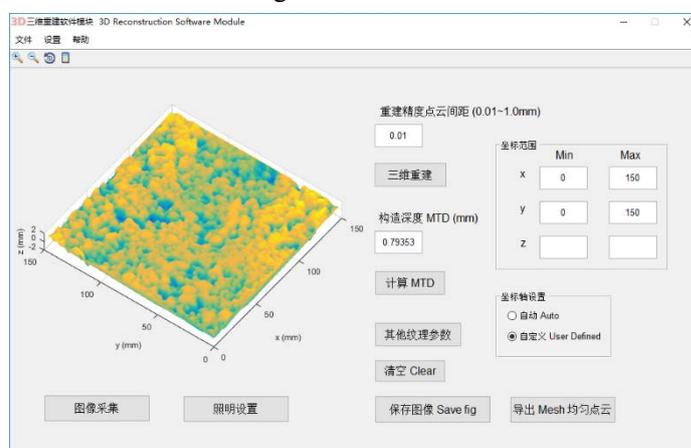


Fig. 3. 3D reconstruction software module

The following steps are required for the process of the software module design:

(1) Camera calibration and external parameter input

On the CRP platform, the camera external parameters such as the matrix R , T of the camera coordinate system are obtained by camera calibration, fixed camera angle and azimuth. The camera external parameters are used as the known input parameters to calculate the spatial coordinate points [12].

(2) Image adjustment

Image adjustment includes image distortion elimination [13] and adjustment of image brightness, contrast. Image distortion elimination model is:

$$\begin{aligned} \Delta x &= (x-x_0)[k_1r^2+k_2r^4]+p_1[r^2+2(x-x_0)^2] \\ &+2p_2(x-x_0)(y-y_0) \\ \Delta y &= (y-y_0)[k_1r^2+k_2r^4]+p_2[r^2+2(y-y_0)^2] \\ &+2p_1(x-x_0)(y-y_0) \end{aligned} \quad (4)$$

Among them, Δx , Δy are the image point displacement caused by the distortion of images, (x_0, y_0) is the image main point coordinate (intersection of the perpendicular of the center of photography and the image plane and the image plane). $r^2 = (x-x_0)^2 + (y-y_0)^2$, k_1 , k_2 , p_1 , p_2 are the radial distortion coefficient, and they are known parameters of the lens.

(3) Point cloud reconstruction and registration

Based on the matching of feature points between images, the coordinates of space point cloud data [14] are calculated by the SFM algorithm. If the coordinate of projection point g_m of space point G_i on the two-dimensional coordinate system where the camera seat is located in, is (x_m, y_m) , then the projection of all spatial points set G in n th frame image are:

$$\begin{pmatrix} x_{i1} & \dots & x_{in} \\ y_{i1} & \dots & y_{in} \end{pmatrix} = R \begin{bmatrix} X_1 & \dots & X_i \\ Y_1 & \dots & Y_i \\ Z_1 & \dots & Z_i \end{bmatrix} + T \quad (5)$$

Among them, (X_i, Y_i, Z_i) is the three-dimensional coordinate of the space point G_i , R is the rotation matrix of every two camera positions and T is the translation vector. They can be obtained by matching the feature points between the images (see section 1.1). Assume the minimum spacing between point cloud data is 0.01mm, the process of point cloud reconstruction to obtain a spatial point three-dimensional coordinate is shown in Figure 4. At the same time of point cloud reconstruction, the point cloud registration algorithm based on Iterative Closest Point (ICP) is used to register the point clouds, and the points cloud is transformed into the same coordinate system. Then search for an optimal geometric transformation that allows multiple point cloud data to be convergent in the same coordinate system as good as possible.

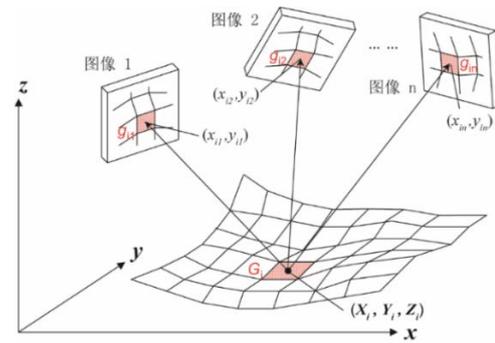


Fig. 4. Point cloud reconstruction to obtain the 3D coordinate of space point

(4) Generate 3D Texture model

After completing the calculation of the cloud points (figure (a)), the triangular meshing is done (figure (b)) and the 3D texture model (figure (c) (d)) is generated. For the three-dimensional texture model, the model scale needs to be further adjusted. The local axis properties need to be defined. Hole filling correction and plane leveling are required as well.

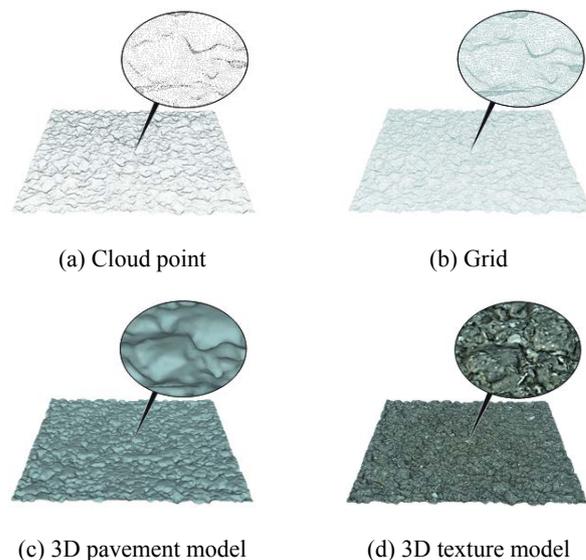


Fig. 5. Generating process of 3D pavement texture model

3 Field testing

Select Nanjing Jiangning District Liangjiang East Road for field testing, Liangjiang East Road is a two-way two-lane road (South-North direction /north-south direction), asphalt mixture grade is AC-13.

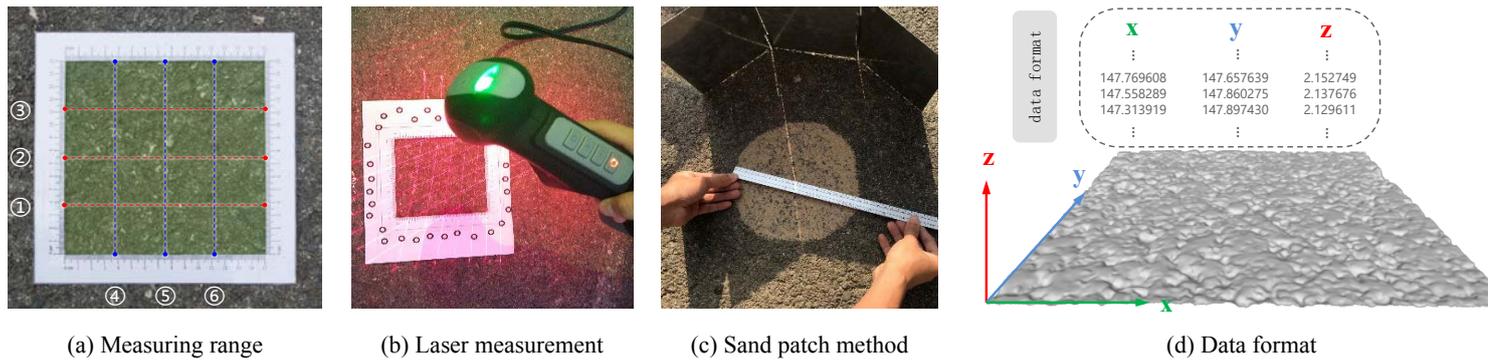


Fig. 6. Measuring range and data format reconstruction

3.1 Data acquisition

The surface texture parameters were collected using ACRP System, laser measurement (Fig. 6(b)) and sand-patch method (Fig.6(c)). For the close range photogrammetry, the paper uses the proposed ACPR system to complete the road image acquisition and three-dimensional reconstruction. The test uses the ZGScan 717 PLUS industrial handheld laser scanner to obtain a three-dimensional model of the object to be tested directly, with an accuracy of 0.02mm (Figure 6 (b)).

The three-dimensional model of the obtained pavement is processed and analyzed, including the fill hole correction, leveling, defining the local axis properties. Then exporting the texture three-dimensional elevation data (Figure 6 (d)) including xyz 3D coordinates from the three-dimensional model of the pavement texture model. Texture elevation data with the same format can be obtained by using a post-processing procedure similar to that of the close range photogrammetry.

3.2 Anti-skid evaluation index

In this paper, two texture parameters including the mean texture depth (MTD) and root mean square roughness (RSMR) are selected to evaluate the asphalt pavement surface anti-skid performance. The calculation coverage of MTD is shown in Fig.6 (a), which is a 150mm×150mm square area. The calculation profiles of RSMR are indicated by the dashed lines in Fig 6 (a), which are 25%, 50%, 75% of the edge length, 6 profiles in total.

The mean texture depth is calculated as:

$$V = \iint_D [F_0 - F(x, y)] dx dy \quad (6)$$

$$MTD = \frac{V}{A} \quad (7)$$

Where, F_0 is the space plane covering on the road surface, $F(x, y)$ is the area formed by the elevation point of the pavement, D is the integral area, V (mm^3) is the volume enclosed between the road pavement and the plane F_0 , and A (mm^2) is the area of the integral area D .

The formula for calculating the root mean square roughness (RSMR) is:

$$RMSR = \sqrt{\frac{1}{N} \sum_{i=1}^N [z(x_i)]^2} \quad (8)$$

Where, $z(x_i)$ is the profile elevation point shown in Figure 6(b). Considering the accuracy of the road surface texture measurement results, the pavement texture is first tested by close range photogrammetry and laser measurement, and then the MTD value of the road pavement is measured by the sand patch method.

4 Method validation

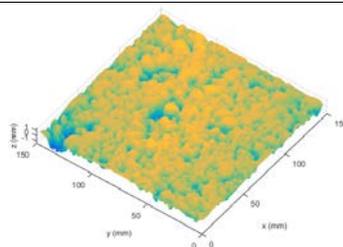
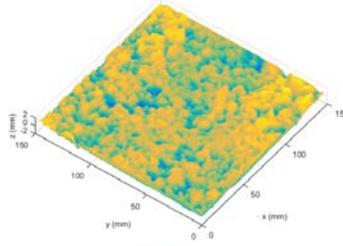
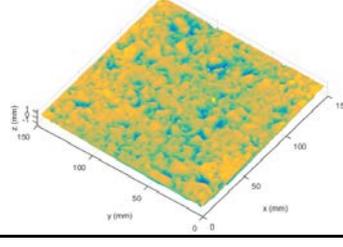
4.1 Accuracy of close range photogrammetry system

The pavement texture parameters obtained by the laser measurement (ZGScan) and the sand patch method are compared with those of the CRP system, as shown in Tables 2 and 3. It can be seen from Table 2 that based on the results from the ZGScan handheld industrial laser scanner, the RSMR index obtained by the ACRP system

basically reaches the ZGScan accuracy. The measurement results from the ACRP system are larger on

the whole, and the mean relative error (MRE) is -0.29%, -0.31%, -0.14%, respectively.

Table 2. Calculation results of statistical index RSMR of asphalt pavement texture parameters

P	3D Texture	Profile	RSMR (mm)		Statistical Parameter			
			Benchmark	Validation	AE (mm)	MAE (mm)	RE	MRE
			ZGScan	ACRP System				
1		①	0.0982	0.0986	-4.0E-04	-2.83E-04	-0.41%	-0.29%
		②	0.1107	0.1100	7.0E-04		0.63%	
		③	0.1030	0.1050	-2.0E-03		-1.94%	
		④	0.0868	0.0871	-3.0E-04		-0.35%	
		⑤	0.1106	0.1110	-4.0E-04		-0.36%	
		⑥	0.1057	0.1050	7.0E-04		0.66%	
2		①	0.1175	0.1180	-5.0E-04	-3.67E-04	-0.43%	-0.31%
		②	0.1046	0.1050	-4.0E-04		-0.38%	
		③	0.0893	0.0889	4.0E-04		0.45%	
		④	0.1193	0.1190	3.0E-04		0.25%	
		⑤	0.1020	0.1030	-1.0E-03		-0.98%	
		⑥	0.1300	0.1310	-1.0E-03		-0.77%	
3		①	0.0895	0.0898	-3.0E-04	-1.17E-04	-0.34%	-0.14%
		②	0.0742	0.0743	-1.0E-04		-0.13%	
		③	0.0925	0.0929	-4.0E-04		-0.43%	
		④	0.0816	0.0813	3.0E-04		0.37%	
		⑤	0.0703	0.0706	-3.0E-04		-0.43%	
		⑥	0.0853	0.0852	1.0E-04		0.12%	

Note: P: Point; RSMR: Root mean square roughness; AE: Absolute error; MAE: Mean absolute error; RE: relative error; MRE: Mean relative error.

Table 3. Calculation results of statistical index MTD of asphalt pavement texture parameters

S	MTD			Statistical Parameter			
	Benchmark I	Benchmark II	Validation	AE (mm) (I)	RE (I)	AE (mm) (II)	RE (II)
	Sand patch	ZGScan	ACRP System				
1	0.94	0.9310	0.9265	1.6E-02	1.72%	4.5E-03	0.48%
2	0.75	0.7675	0.7691	-1.7E-02	-2.29%	-1.6E-03	-0.21%
3	0.88	0.8611	0.8670	1.5E-02	1.67%	-5.9E-03	-0.69%
4	0.55	0.5350	0.5420	4.9E-03	0.90%	-7.0E-03	-1.31%
5	0.67	0.6710	0.6648	9.6E-03	1.42%	6.2E-03	0.92%
6	0.64	0.6129	0.6051	3.1E-02	4.83%	7.8E-03	1.27%
7	0.49	0.4790	0.4811	8.4E-03	1.72%	-2.1E-03	-0.44%
8	0.45	0.4403	0.4446	8.7E-03	1.91%	-4.3E-03	-0.98%

Note: S: Road section.

The data in Table 3 shows that the ACPR system has high measurement accuracy and the relative error (RE) is within $\pm 5\%$, based on the MTD values obtained

by the sand patch method and ZGScan, respectively. In addition, the MTD values obtained by the ZGScan and ACRP system are smaller than that of the sand patch

method. This is because the laser measurement and the close range photogrammetry are all based on the principle of light propagation which cannot capture the partially hidden curved tunnel and fine seams of the asphalt mixture during the data acquisition process. Therefore, the calculated filling volume of the imaginary sand is smaller. The sand patch method is to fill the pavement texture with a fixed volume of test sand, which can better measure the MTD value of the close-graded pavement.

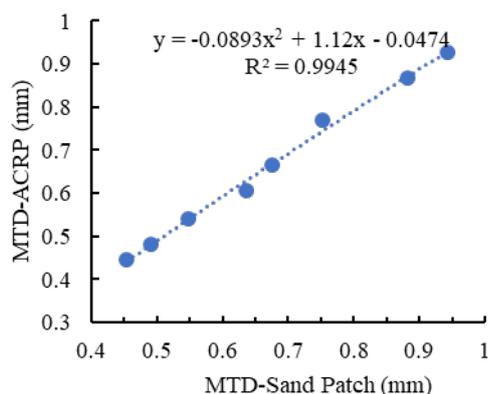


Fig. 7. Correlation analysis between the results of the sand patch method and the ACRP system measurement

The correlation analysis between the results of the sand patch method and the ACRP system measurement is shown in Fig. 7. After eliminating the abnormal data, R^2 reaches 0.9945, which indicates that the ACRP system proposed in this paper can collect high-precision asphalt pavement texture, and can replace the sand patch method to collect the pavement texture MTD value.

4.2 High efficiency of close range photogrammetry system

Statistical analysis was carried out on the time taken to collect texture information by ACRP system, ZGScan and sand patch method. The interval of the reconstructed cloud points was set to be 0.01 mm, and the test time of single-point sand patch was recorded. The statistical data is shown in Fig. 8. The data shows that the time ACRP system consumed to obtain the surface texture of the asphalt pavement and calculate the texture parameters is much less than that of the ZGScan and the traditional sand patch method, which means ACRP system can efficiently complete the surface texture parameter measurement of the asphalt pavement.

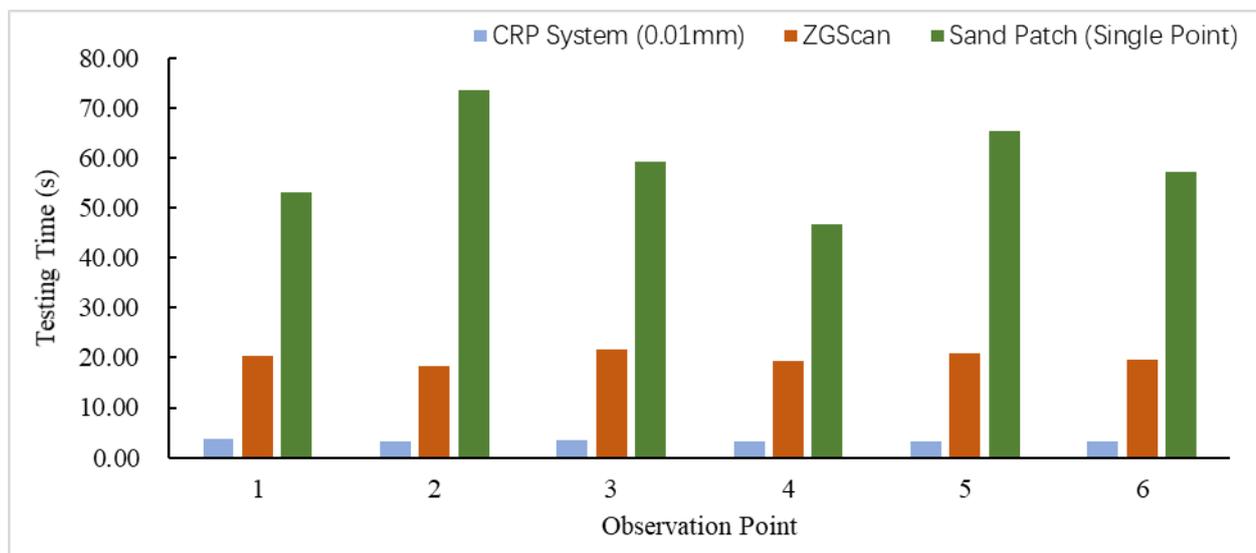


Fig. 8. Time consumption of each test method

5 Conclusion

(1) The ACRP platform determines the orientation and relative position of the three cameras, and can solve the coordinates of spatial points by using the camera

external parameters R 、 T matrix as known parameters. Compared with the traditional close range photogrammetry technology, there is no need to solve the external parameters R 、 T matrix, which improves the efficiency of acquisition and measurement.

(2) The ACPR system is used to test the asphalt pavement texture information on site, and the obtained result is compared with those of laser measurement (ZGScan) and sand patch method. The MRE values are all within $\pm 0.5\%$, and the RE values are all within $\pm 5\%$. The RSMR and MTD indicators obtained by the ACRP system can achieve the accuracy requirement of the ZGScan handheld industrial laser scanner.

(3) Through the correlation analysis, the MTD value extracted by the ACRP system has a good linear correlation with that of the sand patch method. Compared with the sand patch method, the MTD obtained by the ZGScan and CRP systems are smaller.

In summary, the ACRP system based on CRP technology proposed in this paper can collect high-precision asphalt pavement texture efficiently in real time, which greatly improves the working efficiency and accuracy of traditional close range photogrammetry. It can provide subsequent driverless vehicle braking studies with real-time and efficient pavement texture parameters.

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