Detecting device and technology of pavement texture depth based on high precision 3D laser scanning technology

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Abstract. The pavement means texture depth (MTD) is part of the most significant indexes to the characteristics of the pavement macrostructure. Traditional measuring MTD methods are easily impacted by the human factors with inefficiency and low-accuracy. In order to realize the automatic detection of the MTD, a high precision asphalt pavement MTD detection system is built based on three-dimensional line laser scanning, and a MTD calculation method based on the line laser three-dimensional (3-D) data is proposed. Firstly, the 3-D elevation data are extracted from the obtained linear structure light images. Secondly, a denoising algorithm based on two-way standard deviation filter is presented for the 3-D elevation data. Finally, a MTD calculation method based on the line laser 3-D elevation data is designed. The MTD of five asphalt specimens with different roughness was measured by the calculation method designed in this study and sand patch measurements, respectively, and the results were comparable. The research demonstrates that the error between the calculation result of this algorithm and that of sand patch measurements is not more than 5%, which further proves the feasibility of this algorithm.

1. Introduction

Nowadays, the development of the pavement has been transformed from construction to detection and maintenance. How to maintain and manage such a large-scale road network and how to test the performance of the road has become an important issue in road construction in China. The complex road condition and the underdeveloped image acquisition software and hardware technology make the achieved pavement images with high noise; it brings difficult image processing and low detection. Many researchers devote themselves to the fast, correct and efficient evaluation of the safety performance of the pavement surface, among which the texture depth (TD) as the most important indicator has been widely studied.

Numerous studies show that the pavement texture depth is one of the important indexes for evaluating pavement performance[1-4]. Within the wavelength range of macro-texture, 0.5-50mm, the most significant influence of texture is in the fields of rolling resistance, tire-road friction and noise[5]. The evaluation of pavement structure can be used to identify areas where friction performance of pavement may not meet the friction requirements, thus supporting the reduction of accidents[6]. For asphalt pavement, areas with uneven surface texture are segregation indicators, which often lead to poor pavement performance[7]. The maturity and development of digital image technology provide a new way for texture detection of asphalt pavement. Although digital image processing technology improves the efficiency of pavement damage detection, it depends on the accuracy of imaging equipment, and cannot be used for high-precision identification. Based on the principle of laser triangulation[8,9], three-
dimensional machine vision measurement using structured light and planar CCD cameras is gradually emerging and applied to damage detection and three-dimensional image reconstruction and other fields. It is noted that the measuring range of this method is 50μm[9]. Based on three-dimensional laser scanning pavement data, it can effectively detect typical damages under different road conditions and environments, and the detection accuracy is over 98%[10]. The traditional sand patch measurements method is used to measure the mean texture depth of asphalt pavement, but its accuracy is low and it is difficult to satisfy the needs of practical engineering. Therefore, more innovative methods are needed to characterize the three-dimensional texture of asphalt pavement[11].

Based on the problems of low efficiency and low precision of pavement detection, the paper combines digital image technology with three-dimensional laser scanning technology to measure and calculate the pavement texture depth, which provides a reference for fast and accurate calculation of pavement texture depth. An algorithm for automatically estimating road roughness from three-dimensional laser scanning data is proposed. The algorithm is helpful for a more comprehensive measurement of road structure depth. By comparing and analyzing several kinds of pavement data acquisition sensors, this paper puts forward the pavement crack identification technology based on CCD camera, and studies how to use digital image processing technology to solve the problem of pavement damage automatic identification.

2. Experimental

2.1 3D laser scanning measurement principle

Laser triangular method is one of the most common optical three-dimensional measurement techniques that calculate the displacement on the camera sensor due to the position of the pavement surface reflection points. Line laser is projected into a bright line on the object surface under test. The camera acquires an image for each forward 0.1mm, which can obtain all the three-dimensional data on the object surface contour, and calculates the three-dimensional height information by the triangulation method. The laser emits a laser that is reflected on the object surface, then the laser beam goes through the lens, the light energy is collected through the photosensitive element, and finally, the imaging system is imaged. When the position of the object surface is changed, the corresponding displacement occurs in the imaging system. According to the relationship between the image displacement and the real displacement, the actual object displacement is calculated by detecting the image displacement. The principle of the laser triangulation method is illustrated in Figure 1(a). The angle between the axis of the line laser and the axis of the camera is theta θ, the focal length of the camera is f, the distance between the transmitting lens and the receiving lens is L, the distance from the receiving lens to the reference point is a, and the variation displacement of the real depth of the object surface is x. The change in the displacement of the depth change on the target surface of the camera is represented by x'.

In triangle AOB, according to sine law:

\[
\frac{a}{\sin(\theta-a)} = \frac{x}{a}
\]

(1)

where a is the distance from the receiving lens to the reference point, x is the displacement of the real depth of the object surface, θ is the angle between the line laser axis and the camera axis, a indicates the angle due to the change of object position.

After reorganizing the formula, one gets the Equation (2):

\[
x = \frac{a}{\sin\theta cot\theta - \cos\theta}
\]

(2)

In right triangle COD, substituting parameters cotα=a/L'，sinθ=L/a，cosθ=√(a^2-L^2)/a into Equation (2), then the variation displacement x of the real depth of the object surface is obtained,

\[
x = \frac{a^2 x'}{L f x' \sqrt{a^2-L^2}}
\]

(3)

Where f is the focal length of the camera, L is the distance between the transmitting lens and the receiving lens, x' is the displacement on the camera sensor due to the position of the pavement surface reflection points, and Lf>>x'√(a^2-L^2), therefore,
\[ x = \frac{a'^2 x'}{L f} \]  

2.2 Pavement surface images acquisitions

A quasi-static and high-precision pavement damage detection device is set up in the laboratory. The detection device includes a movable detection vehicle, an electric linear screw, a surface scan camera, a linear laser illumination device, a photoelectric rotary encoder, an uninterrupted power supply (UPS) device and an Industrial Personal Computer (IPC), as shown in Figure 1(b). The scan camera is used to obtain the optical image of asphalt pavement and the three-dimensional elevation data of the pavement surface is extracted according to laser three-dimensional scanning technology. The line laser illuminator in this device is a near-infrared light laser which can effectively prevent the influence of other light sources on image uniformity, and it provides auxiliary lighting for the camera.

The rotary encoder outputs 100 pulse signals per turn. When the camera moves forward 0.1mm, the rotary encoder sends out a pulse signal that triggers the camera to work, and then the camera collects a light image of the pavement surface. The UPS provides power for the detection device. The IPC as the core part of the detection device undertakes the main task of image data acquisition, image processing, and image data statistics. In order to avoid the inconvenience caused by the disassembly of the camera and line laser, they are fixed as a whole. The electric linear screw module is the power system of the detection device. The stepper motor of electric linear screw module drives the screw, and the reciprocating motion of the slider on the screw is controlled by the control switch. The moving slider on the screw keeps the camera and the line laser maintains relative movement to the object. At the same time, the axis of the camera and the axis of the line laser are in an angle of 30°, and their axes are coplanar and the plane is perpendicular to the horizontal plane.

The pavement data collection steps of the pavement detection device are as follows:

1. Five kinds of asphalt specimens were prepared, which were the maximum particle size of 9.5mm micro surface (MS), 9.5mm ultra-thin wearing course (UTWC), and 13.2mm stone matrix asphalt (SMA), 16mm rubber asphalt concrete (RAC) and 16mm dense graded asphalt concrete (AC), respectively. Their sizes are all 300mm×300mm×50mm. The experimental location is in the civil engineering and transportation engineering laboratory of Nanjing, Jiangsu Southeast University Jiulonghu Campus (31.89°N, 118.82°E);

2. The reset switches are installed on both ends of the module screw because the reset switches control the effective displacement of the slider. The stepper motor, the device driver, the controller, and the reset switch is connected correctly. The power supply equipment was started to make the electric linear screw module in a standby state after making sure it is correct;

3. The reset switches of the electric linear screw are controlled by manual control to make the slider reciprocate, and the effective displacement of the tested pavement could be roughly determined;

4. The encoder is connected to the camera through the data line, same as the camera is connected to the Industrial Personal Computer. The encoder, the camera, the Industrial Personal Computer, and the linear laser are all connected to the power supply device;

5. The inspection vehicle was placed on the damaged road surface and the small sealing handle equipped with the camera and the line laser was rigidly attached to the slider;

6. Open the industrial computer, open the image information collection software in the industrial computer, and set the parameters;

7. The reset switch of the electric linear screw is controlled by a manual control method, so that the slider drives the small sealed box equipped with the camera and the line laser to reciprocate and collect road information.

8. The road surface information collected by the camera is converted into a hard disk of the industrial computer through the conversion of the Gigabit Ethernet card;

9. The three-dimensional height data were calculated from the structured light image stored in the hard disk according to the three-dimensional laser scanning technique.
2.3 A digital image processing methods
Due to factors such as diffuse reflection of the exposed pavement aggregates and jitter of the detection system equipment, the collected pavement data are inevitably affected by noise, which causes the collected 3D data to deviate from the real depth value at different levels. Noise distribution contains the following characteristics. One is that the standard deviation of noise is much greater than the standard deviation of useful data, and the other is that the noise has strong randomness, and it exists in the whole data space, not only in the linear range of single-dimensional and on the two-dimensional plane. In view of this, this paper uses the "biphasic standard deviation filtering method" to perform row and column filtering on 3D data. The main idea of bidirectional standard deviation filtering is to scan the data matrix from two directions respectively and to use certain filtering conditions to judge and filter the original 3D data containing noise, and to retain the useful data to filter out the noise data so as to obtain the filtered data matrix. Specific steps are as follows,

Firstly, the data of the three-dimensional image data matrix $A_{\text{new}}$ are read row by row, and the data in the $i$ row are recorded as $R_i=(Z_{i1},Z_{i2},...,Z_{in})$ and $i=(1,2,...,n)$, and the arithmetic mean and standard deviation of $R_i$ are calculated from equations (5) and (6), respectively:

$$\bar{R}_i = \frac{\sum_{j=1}^{n} (Z_{ij} + Z_{i2} + ... + Z_{in})}{n}$$

$$S_i = \sqrt{\frac{(Z_{i1}-\bar{R}_i)^2 + (Z_{i2}-\bar{R}_i)^2 + ... + (Z_{in}-\bar{R}_i)^2}{n-1}}$$

Secondly, each data $z_{ij}$ in the row is taken in turn. If $|z_{ij}| > k$, the arithmetic mean value $R_i$ is used instead of the point data value $z_{ij}$, $k$ represents the filtering factor, and $k$ is 1.6.

Finally, noise points are eliminated again by column processing in the same way. After all, rows are processed; the 3D data matrix $E$ after bidirectional standard deviation filtering is obtained.

2.4 A principles of texture depth calculation
The pavement means texture depth is the most important indicator of the anti-sliding performance. The basic idea of the MTD calculation method based on 3D line laser scanning is presented. First, a datum is determined, then the volume of the irregular graph formed by pavement and datum is calculated according to the idea of traditional volume method, and then the MTD value can be obtained by splitting the volume by the area of the region. By building structural elements to fit the datum, the selection of the base level determines the feasibility of the algorithm. For the fitting of pavement datum, the structural elements selected by morphological filtering are first determined and used to generate the datum. In order to consider the rationality of the selection of the structural elements, two kinds of structural elements are selected for comparison, that is, the rectangular structural element (R) and the
spherical structural element (S). The operation mode is the closing operation, which is the first dilation and then erosion:

$$m \odot n = (m \circ n) \ominus n$$  \hspace{1cm} (7)

Firstly, the size of the structural elements is established according to the size of the matrix. For the rectangular structural element, the parameters of the length l and the width b should be determined. For the spherical structural element, the radius r of the circle projected on the x-y plane and the maximum offset height h should be determined. Secondly, according to the generated structural element, the gray scale image is expanded first and then corroded by the morphological closing operation, and the dilation and erosion are operated by the same structural element to form the pavement fitting surface. Then, the volume between the simulated datum and the irregular three-dimensional surface after filtering is calculated, and the MTD value can be obtained by dividing the volume by the area of the region. The spherical structural element is utilized to generate a spacing surface fitted with the original pavement, but this has a high requirement for the parameter selection of the spherical structure element.

By filtering and plane fitting, a new spatial model function is obtained,

$$Z = F(x, y)$$  \hspace{1cm} (8)

Where x and y are the horizontal and vertical coordinates of the spatial point. A circular region $D$ is selected optionally mapped by a spacing surface in the X-Y plane, and the volume size of the spatial surface built by the spatial model in $D$ of the circular region and the spatial region mapped to the datum $Z_0$ is calculated, namely,

$$V = \iint_D [Z_0 - F(x, y)] \, dx \, dy$$  \hspace{1cm} (9)

Where $V$ is represented as the volume of the space surface and the datum $Z_0$, and the ratio of volume $V$ to area $D$ is the MTD value of the area to be measured, that is,

$$MTD = \frac{V}{D}$$  \hspace{1cm} (10)

3. Results

3.1 Pointed cloud data filtering

The pointed cloud data denoising process is realized by the MATLAB secondary development program based on the bidirectional standard deviation filtering. Figure 2(a) is a three-dimensional model diagram of the surface of an ultra-thin wearing course (UTWC) with a maximum aggregate size of 9.5 mm. The macroscopic performance is that the surface is rough and the "void" is more. (b) is a three-dimensional model diagram of the surface after filtered., the surface depth is more uniform after the filtering process, which is more satisfied with the actual situation of the pavement. The surface depth at different positions is within 2 mm. However, the study concluded that the filtering factor directly affects the pavement mean texture depth value. The larger the filtering factor, the larger the mean texture depth value. This is because the points satisfying the equation $|z_{ij} - R_{il}|/si > k$ are less, and the filtering has less influence on the original data.

After many calculations, UTWC selects the filtering factor $k=1.6$. When the filtering factor $k=1.6$, the error between the calculated texture depth value and the value calculated by the ellipsoid element fitting datum plane is within 5%.

![Figure 2](image.jpg)  \hspace{1cm} Figure 2. Comparison of 3D models before and after filtering.
The program design is completed as required. Each group of data transferred to the program is filtered in turn by the program, and the three-dimensional model of the pavement surface is built according to the filtered data, and the datum is built at the same time. The fitting datum of different structural elements is shown Figure 3.

3.2 Texture depth calculation

Figure 4 shows the pavement surface means texture depth values of different types of asphalt mixture specimens. These values are calculated on the basis of digital image technology. Figure 4(a) shows that the measured value is compared with the calculated value, and the results show the calculated mean texture depth value of the calculation method is consistent with the measured value, so the MTD of asphalt pavement can be calculated by using the method of fitting the datum surface. Figure 4(b) represents the MTD value based on the datum of the morphological filter rectangular structure element and spherical structure element. At the same time, different filter factors are selected for different asphalt mixture specimens. It is found that the MTD values calculated by the two methods are similar, which shows that the datum of spherical structure element can also be used to calculate the MTD of the pavement surface, and achieves good results. However, the pavement datum formed by the fitting of the rectangular structure element is terraced, which is not consistent with the actual situation. Therefore, the method of using the rectangular element to fit pavement datum is debatable. (b) shows the pavement surface MTD fitting curve calculated by two different methods. The study found that the two calculation results had a high degree of linear correlation. And the correlation coefficient R²=0.998. At the same time, it is found that the ultra-thin wearing course (UTWC) with a maximum particle size of 9.5mm has the largest MTD value of 1.7986mm. The MTD value of the maximum particle size of 13.2mm stone matrix asphalt (SMA) is minimal, only 0.8516mm. In the dense asphalt concrete mixture, whether there is a certain relationship between the MTD value of the pavement surface and the size of the grading, more experimental verification is needed.

4. Conclusions

This research is mainly divided into three distinct parts. First of all, according to the research is required to determine the equipment parameters and build indoor detection device. Secondly, three-dimensional data are obtained. Then, the image filtering processing is carried out by MATLAB and the pavement surface 3D Reconstruction for the region to be measured is built. Finally, the mean texture depth of the pavement structure is calculated according to the fitting datum of the rectangular element and spherical element, which is compared with the MTD value measured by the volume method. It is well known that the pavement surface texture can affect surface properties, tire-to-vehicle interactions, and road safety. According to the experimental and calculation model, the following conclusions are drawn.

![Figure 3. Fitting planes of different structural elements.](image)

![Figure 4. Comparison of texture depth values calculated by two different methods.](image)
The indoor quasi-static high-precision pavement detection device was built, and the experiment was carried out by five different types of asphalt mixture specimens. The research shows that the experimental device can meet the indoor testing requirements and can be used to detect the pavement distress;

According to the standard deviation comparison before and after filtering, it can be found that the bidirectional standard deviation filtering can filter out noise better, but the filtering factors selected by different road types are different, and the pavement mean texture depth calculated by different filtering factors is different;

The calculation method of asphalt pavement texture depth based on three-dimensional information is designed. The experimental results demonstrate that the algorithm has good stability and high reliability.

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