A Metrological of Laser Pavement 3D Measurement Equipment

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Abstract. Laser pavement 3D measurement equipment is widely used in pavement measurement due to its comprehensive, fast and reliable measurements. In the study, based on the working principle and measurement output indicators of laser pavement 3D measurement equipment and the analysis of influencing factors, reasonable metrological indicators were determined firstly. Then, a convenient, efficient, and reliable test method was developed based on the determined metrological indicators to provide the basis for calibrating objects and preparing metrological standards. In addition, through the survey from partial users in China, the measurement errors of existing equipment were evaluated. The study provides the basis for subsequent establishment of metrological standards for pavement 3D measurement equipment.

1. Introduction

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Due to the large-scale construction of highways in China in the past three decades [1], the total length of highways has increased to 5,0125 million kilometers until the end of 2019 and the total length of expressways has increased 149,600 kilometers and ranks first in the world. At present, Chinese highways require extensive maintenance, mainly depending on pavement flatness, rutting, distress and other parameters. The high-precision measurements of various pavement parameters are the basis for pavement maintenance and the reliability of the pavement measurement technology depends on standardized metrological methods and metrological standards.

At present, Chinese pavement measurement technologies are mature and some technical indicators are even in the leading ranking in the world. Current pavement measurement technologies are mainly based on the non-contact rapid laser detection method, in which flatness, rutting, distress and other indicators of pavement are quickly determined mainly with a multi-functional pavement condition measurement vehicle. However, such a measurement vehicle is currently limited to the two-dimensional measurement stage of a single indicator. The measurement vehicle has three independent subsystems which respectively detect three parameters. Typical road measurement systems include the ZOYON-RTM intelligent road condition detection system produced by Wuhan Wuda Zhuoyue Technology Co., Ltd. [2] and CICS multifunctional pavement detection system [3] produced by Research Institute of Highway, Ministry of Transport. Flatness and rutting are currently measured by spot laser and road damages are mainly recognized by the two-dimensional optical image method. Available metrological and calibration regulations released by Ministry of Transport include Vehicle Bearing Road Laser Profilometer (JTG 075-2010) [4], Vehicle Bearing Road Laser Rut-meter (JTG
Vehicular Video Detecting System for Pavement Distress (JJG 077-2010) [6] and related calibration indicators mainly include measurement ranges, indication errors of laser sensors, repeatability, and the resolution of the road distress image for the reliability evaluation of pavement detection equipment [7].

In recent years, due to the continuous development of computer technology and sensor technology, laser pavement three-dimensional detection equipment can comprehensively, quickly and reliably detect the changes in the pavement conditions and has been applied in pavement detection. However, due to insufficient technologies development and unqualified equipment quality, it has not been widely promoted. Therefore, it is urgent to analyze the working principles and measurement output indicators of laser pavement 3D measurement equipment as well as related influencing factors for the purposes of determining reasonable metrological indicators and supporting subsequent establishment of metrological standards.

2. Optical Three-Dimensional Measurement Technology

Commonly used optical three-dimensional measurement involves three basic principles [8]: time-of-flight method, interference measurement and triangulation [9].

In the time-of-flight method, the distance is acquired with measured flight time of light waves and then three-dimensional surface shape data are obtained through scanning the entire surface of an object with light pulses from the additional scanning device.

In the interference measurement method, a coherent beam is firstly divided into the measurement beam and the reference beam and then the phase difference between the two beams is determined through the coherent superposition between them, so that the depth data on the object surface can be obtained. This method has the high measurement accuracy, but the measurement range is limited by the wavelength of light waves. It can measure the surface topography and microscopic displacements, but it is not suitable for the detection of macroscopic objects. Therefore, it is not suitable for road detection.

Optical triangulation is the most commonly used optical three-dimensional measurement technology. Based on laser triangulation displacement measurements, the depth data at a point is calculated with the angular change of the point relative to the optical reference line. When a point structured light is used for illumination, a complete three-dimensional surface shape can be obtained through additional two-dimensional scanning. When a linear structured light is used for illumination, the complete 3D surface shape data can be obtained through only one additional one-dimensional scanning since all the data along a line can be obtained in one measurement. When a surface structured light is used for illumination, 3D surface shape data can be directly obtained.

3. Metrological Indicators

Current studies on pavement detection technologies have experienced the transformations from point lasers to line lasers and surface lasers and from two-dimensional images to three-dimensional images. The laser pavement 3D measurement technology is mainly realized through two parts: lasers and cameras. The laser scans along the pavement and is reflected back to the camera for data acquisition. The scanned data of the pavements obtained by the laser are spliced together to reproduce the three-dimensional structure information of the pavement and then identify roughness, rutting, distresses and other related pavement indicators can be identified. According to Highway Performance Assessment Standards (JTG5210-2018) [10], pavement distresses are mainly classified into cracks, subsidence, rutting, crowding, grooves, patches and other types. Through the analysis of working principles and measurement output indicators of laser pavement 3D measurement equipment, the relevant metrological indicators were preliminarily determined in the study. Laser 3D measurement equipment should consider the measurement accuracy in three dimensions, including horizontal and vertical resolutions and depth measurement accuracy. In addition, the performances of reconstructing images should also be tested, mainly including the recognition accuracy of key types of road distresses. Based on the above-mentioned metrological indicators, standard devices suitable for three-dimensional
detection were developed, including resolution plates, standard instrument plates simulating cracks, and crowding, grooves and other distress types. These metrological calibrators were all three-dimensional structures, so the depth measurement accuracy could be tested accordingly.

According to the design of the above-mentioned metrological calibrators, in order to verify the calibrators and test the accuracy of pavement 3D laser measurement equipment, our group measured the above metrological calibrators with the laser 3D multifunctional vehicle. Corresponding length, width, depth and area of metrological calibrators were respectively obtained in order to verify the error relative to standard values.

Our group selected a road in Wuhan, placed three-dimensional metrological calibrators such as resolution plates, standard crack plates, standard crowding plates and standard groove plates on the road, and analyzed the calibrators with pavement 3D laser detection vehicles, which were mainly based on optical triangulation and adopted line structured light to scan the road direction in order to form complete 3D surface data. Five vehicles with the same configuration were used in the subsequent experiments and respectively recorded as Vehicle 1 to Vehicle 5. The five vehicles passed the selected road three times at a constant speed of 50 km/h and relevant testing data and images were obtained.

3.1. Style and spacing
In the image resolution plate (Figure. 1(a)), grooves with different widths (1 mm, 2 mm, 3 mm, and 4 mm) were distributed in both horizontal and vertical directions and the grooves were 0.5 mm deep. Based these grooves, minimum recognition depth and the horizontal and vertical resolutions of images were determined. Figures. 1(b) and 1(c) are the grayscale image and depth image of the resolution plate. The 1 mm or 2 mm wide grooves are not clearly recognized and the smallest width of distinguishable grooves was 3 mm (Figure. 1(b)). The vehicle could recognize 0.5 mm deep grooves (Figure. 1(c)).

![Resolution Plate](image)

Figure. 1. Schematic diagrams of a resolution plate: (a) design image, (b) grayscale image, and (c) depth image.

3.2. Simulated Crack Plate
Firstly, different types of simulated crack plates such as horizontal cracks, longitudinal cracks, block cracks, and crack network, were placed on the tested road. The plates were designed with irregular cracks of the same depth and width. The depths and widths of cracks were respectively assigned with a levelling instrument and a digital micrometer. The lengths of strip-shaped cracks were indirectly assigned with a piece of soft rope. According to Highway Performance Assessment Standards (JTG5210-2018) [9], the area affected by cracks and the average width of cracks on pavement were calculated for the statistical analysis. As for horizontal and vertical cracks, the affected area was equal to 0.2 times of the length of cracks. As for block cracks and crack network, the area of corresponding circumscribed rectangle was considered as the affected area. The vehicle-mounted laser three-dimensional inspection system output the average width, depth and area of all cracks in the simulated crack plates. Figures. 2(a)-2(f) show the output images of crack plates and Tables 1 and 2 show the measured data, standard values and relative errors.
Figure 2. Examples of the verification method for simulated cracked plates.

Table 1 Measured data and standard values of simulated crack plates

| Serial numbers of cracks | Statistical indicators | Vehicle 1 | Vehicle 2 | Vehicle 3 | Vehicle 4 | Vehicle 5 | Standard values |
|--------------------------|------------------------|----------|----------|-----------|-----------|-----------|----------------|
| No. 1                    | Average width (mm)     | 3.1798   | 3.1536   | 3.1298    | 3.1224    | 3.151     | 4              |
|                          | Average depth (mm)     | 2.0404   | 1.9162   | 1.867     | 1.8106    | 2.003     | 1.99           |
|                          | Affected area (m²)     | 0.1978   | 0.1976   | 0.1974    | 0.1978    | 0.1976    | 0.194          |
| No. 2                    | Average width (mm)     | 3.1532   | 3.2842   | 3.0014    | 3.236     | 3.1978    | 4              |
|                          | Average depth (mm)     | 1.9724   | 2.0296   | 1.909     | 1.9106    | 1.9894    | 1.9            |
|                          | Affected area (m²)     | 0.278    | 0.278    | 0.2782    | 0.2778    | 0.2784    | 0.2474         |
| No. 3                    | Average width (mm)     | 5.2644   | 5.3004   | 5.0976    | 5.1376    | 5.1738    | 6.15           |
|                          | Average depth (mm)     | 3.115    | 3.1498   | 3.0438    | 3.029     | 3.1096    | 3.56           |
|                          | Affected area (m²)     | 0.2544   | 0.2536   | 0.2548    | 0.2544    | 0.2546    | 0.265          |
| No. 4                    | Average width (mm)     | 3.4676   | 3.4306   | 3.5094    | 3.3892    | 3.5526    | 3.91           |
|                          | Average depth (mm)     | 1.885    | 2.0408   | 1.8172    | 2.0082    | 1.9004    | 1.88           |
|                          | Affected area (m²)     | 0.4384   | 0.4282   | 0.4364    | 0.4374    | 0.4354    | 0.42735        |
| No. 5                    | Average width (mm)     | 5.2138   | 5.1554   | 5.1698    | 5.233     | 5.1824    | 6.15           |
|                          | Average depth (mm)     | 3.005    | 3.012    | 2.9592    | 3.0764    | 2.9852    | 3.6            |
Nos. 1, 2 and 3 cracks were strip-shaped cracks and Nos. 4, 5, and 6 cracks were block cracks (Fig. 2 and Tables 1 and 2). Except the No. 2 crack plate, the other 5 crack plates showed that the relative errors between the affected area and standard values were all within 5%. The relative error of the No. 2 crack plate was 12%. The strip-shaped crack on the No. 2 crack plate could well simulate real cracks and there were small cracks around it (Figure. 2(b)). Therefore, the different identification methods used in the assignment and detection processes led to relatively large errors.

The average width and average depth of cracks were small. Maximum standard width was 6 mm and maximum standard depth was 3.6 mm. Therefore, the relative errors were relatively large. Average width error was within 1 mm and relative error was within 25%. Average depth error was within 0.5 mm and the relative error was within 20%.

### 3.3. Simulated Plates of Crowding and Grooves

Figures. 3(a) and 3(b) show the simulated road crowding and grooves. The height of each step could also be used to detect the error accuracy of laser ranging and the area of each step could be used to
detect the ability of the detection system to identify simulated crowding and grooves. Metal aluminum was used as a standard part during processing. In subsequent experiments, due to insufficient surface roughness, the light reflection and zero-scattering might be easily generated, so sandblasting oxidation treatment was performed on the standard part. Figure. 3(c) shows the scanned image of the standard part output by laser 3D measurement equipment. Since the test pavement might have a relatively large flatness, the outermost steps were selected as the reference surface for laser ranging.

![Figure. 3 Schematic diagram of (a) simulated crowding and (b) simulated grooves as well as (c) scanned images of the standard part.](image)

| Distress types | Serial number of distresses | Statistical indicators | Vehicle 1 | Vehicle 2 | Vehicle 3 | Vehicle 4 | Vehicle 5 | Standard values |
|---------------|-----------------------------|------------------------|-----------|-----------|-----------|-----------|-----------|-----------------|
| Crowding      | The first layer              | Area (m²)              | 0.0196    | 0.0196    | 0.0196    | 0.0196    | 0.0196    | 0.0196          |
|               |                              | Depth (mm)             | 9.998     | 9.984     | 9.98      | 9.924     | 9.998     | 10              |
|               | The second layer             | Area (m²)              | 0.01      | 0.01      | 0.01      | 0.01      | 0.01      | 0.001           |
|               |                              | Depth (mm)             | 19.932    | 20.016    | 20.088    | 19.93     | 19.98     | 20              |
|               | The third layer              | Area (m²)              | 0.0036    | 0.0036    | 0.0036    | 0.0036    | 0.0036    | 0.00359         |
|               |                              | Depth (mm)             | 29.982    | 29.994    | 30.034    | 30.022    | 29.99     | 30              |
|               | The fourth layer             | Area (m²)              | 0.0004    | 0.0004    | 0.0004    | 0.0004    | 0.0004    | 0.00039         |
|               |                              | Depth (mm)             | 34.518    | 34.672    | 34.434    | 34.548    | 34.45     | 35              |
|               | The first layer              | Area (m²)              | 9.996     | 9.948     | 10.014    | 10.002    | 10.012    | 10              |
|               |                              | Depth (mm)             | 0.01      | 0.01      | 0.01      | 0.01      | 0.01      | 0.00999         |
|               | The second layer             | Area (m²)              | 20.01     | 19.946    | 19.988    | 20.012    | 20.062    | 20              |
|               |                              | Depth (mm)             | 0.0036    | 0.0036    | 0.0036    | 0.0036    | 0.0036    | 0.00359         |
|               | The third layer              | Area (m²)              | 30.064    | 29.99    | 29.994    | 29.948    | 30.032    | 30              |
|               |                              | Depth (mm)             | 0.0004    | 0.0004    | 0.0004    | 0.0004    | 0.0004    | 0.00039         |
|               | The fourth layer             | Area (m²)              | 34.422    | 34.406    | 34.616    | 34.452    | 34.436    | 35              |

Table 3 Measurement data and standard values of simulated crowding and grooves.

| Distress types | Serial number of distresses | Statistical indicators | Vehicle 1 | Vehicle 2 | Vehicle 3 | Vehicle 4 | Vehicle 5 | Standard values |
|---------------|-----------------------------|------------------------|-----------|-----------|-----------|-----------|-----------|-----------------|
| Crowding      | The first layer              | Area (m²)              | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%           |
|               |                              | Depth (mm)             | 0.02%     | 0.16%     | 0.20%     | 0.76%     | 0.02%     |                 |
|               | The second layer             | Area (m²)              | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%           |
|               |                              | Depth (mm)             | 0.34%     | 0.08%     | 0.44%     | 0.35%     | 0.10%     |                 |
|               | The third layer              | Area (m²)              | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%           |
|               |                              | Depth (mm)             | 0.06%     | 0.02%     | 0.11%     | 0.07%     | 0.03%     |                 |
|               | The fourth layer             | Area (m²)              | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%     | 0.00%           |
|               |                              | Depth (mm)             | 1.38%     | 0.94%     | 1.62%     | 1.29%     | 1.57%     |                 |

Table 4 Relative errors of measurement data of simulated crowding and grooves.
The relative errors of the areas of the regular crowding and grooves were within 0.5% and the relative errors of their depths were within 2% (Tables 3 and 4). In a word, the errors were small.

3.4. Actual Road Grooves

Since the simulated crowding and grooves were in regular shapes, their relative errors were small and could not fully reflect the performance of pavement 3D laser measurement equipment. Therefore, our group randomly selected three real grooves on the test road to perform the comparative experiment with the HandySCAN 3D Scanner and FARO Focus 3D X330 HDR laser scanner.

The FARO Focus 3D X330 HDR laser scanner obtained the distance from the scanner to the object to be measured by measuring the phase shift of the scattered light reflected from infrared light waves and the ranging error was ±2 mm.

The phase of the scanning grating in the HandySCAN 3D scanner was modulated and deformed with the changing height of the object surface. The phase change containing the height information of the object surface was obtained through demodulation. Then, the relationship between the phase and the object surface height could be determined according to the optical triangulation principle, and the image is obtained by stitching. Finally, the global 3D point cloud image was obtained after splicing. The accuracy of the instrument could reach 0.035 mm, which significantly exceeded the accuracy of existing pavement laser 3D measurement equipment.

| Layer         | Area (m²) | Depth (mm) |
|---------------|-----------|------------|
| The third layer | 0.00% 0.00% 0.00% 0.00% 0.00% | 0.21% 0.03% 0.02% 0.17% 0.11% |
| The fourth layer | 0.00% 0.00% 0.00% 0.00% 0.00% | 1.65% 1.70% 1.10% 1.57% 1.61% |

The area of the No. 1 groove measured by the laser 3D measurement vehicle was 0.192 m² and its standard value and relative error were respectively 0.184 m² and 3.8% (Figure. 4). The area of the No. 2 groove measured by the laser 3D measurement vehicle was 0.57 m² and its standard value and relative error were respectively 0.523 m² and 9.06% (Figure. 5).

![Figure 4](image1)

**Figure 4** No. 1 groove on the actual road: (a) scanning result by the multifunctional vehicle, (b) scanning result by FARO scanner, and (c) scanning result by HandySCAN 3D scanner.

![Figure 5](image2)

**Figure 5** No. 2 groove on the actual road: (a) scanning result by the multifunctional vehicle, (b) scanning result by FARO scanner, and (c) scanning result by HandySCAN 3D scanner.
4. Conclusion
The above experimental results indicated that horizontal and vertical resolutions of the multifunctional laser 3D measurement vehicle were respectively about 3 mm and 0.5 mm. Its detection performance for regular road defects were good and the relative error was within 0.5%. The application of the laser 3D measurement technology in the pavement detection was preliminarily verified. However, the relative errors of irregular defects were about 10%. The ranges of defects have not been provided in relevant domestic standards or regulations. Therefore, it is impossible to determine whether the errors are caused by the inconsistent identification method or the instrumental error. The accuracy of the laser 3D measurement vehicle cannot be further determined.

The above-mentioned problems will be solved in our future study. We will develop unified detection limits and the calibrators of irregular pavement defects, and improve the existing metrological standards in the highway industry in order to better manage and calibrate related laser 3D pavement detection instruments. The study has important research significance for promoting the application of 3D measurement technology in road maintenance.

Acknowledgments
I would like to thank all those who helped me write this paper. I am very grateful to my colleagues, who have given me many valuable opinions and suggestions during my research. During the process of writing the paper, they spent a lot of time reviewing each draft and gave me many inspiring suggestions. Without their careful guidance, this paper would not have been possible.

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