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Research Article

The Research on Obtaining the Geometric Dimension of Cable-Stayed Bridges Based on 3D Laser Scanning

Zhigang Jiang,[1] Lihang Chen ,[2] and Dong Liang [2]

[1]*Hebei Expressway Group Limited, Zhangjiakou 075400, Huailai, Hebei, China*
[2]*School of Civil and Transportation Engineering, Hebei University of Technology, Tianjin 300401, China*

Correspondence should be addressed to Lihang Chen; 202111601012@stu.hebut.edu.cn

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The traditional manual measurement methods are time-consuming and error-prone when they are used for cable-stayed bridges' geometric dimensions acquisition. They are always limited by various adverse conditions such as large bridge spans, the high height of bridge towers, more risk of manual operation, and many other unpredictable factors. In contrast, three-dimensional (3D) laser scanning technology is extremely useful for solving the above problems. After obtaining plenty of point cloud data and point cloud models, precise and accurate geometric dimensions of cable-stayed bridges can be obtained accurately and conveniently. Taking a cable-stayed bridge named XingLinBao as an example, the accuracy and convenience of 3D laser scanning are verified.

1. Introduction

A cable-stayed bridge is a special bridge structure spanning rivers, lakes, seas, and alpine valleys, the components of which are affected by the structure's own weight, environmental loads, cable forces, and temporary construction loads during the field assembly process [1], so the accurate geometric dimensions of components are critical to successfully and smoothly complete cable-stayed bridge installation. To ensure the accurate geometric dimensions of the components, a manual preassembly method is adopted after they are produced [2]. The method always uses manual measurement and manual operation to complete cable-stayed bridges' preassembly process [3]. During cable-stayed bridges' preassembling process, the method is always limited by various adverse conditions such as large spans, the high height of components, more risk of manual operation, and many other unpredictable factors, not to mention the disadvantages of time-consuming, error-prone, and danger [4]. Therefore, a smarter way to measure components' geometric dimensions is urgently needed.

In contrast, as a real scene replication technology, 3D laser scanning technology has many advantages in measuring components' dimensions, such as fast scanning speed, wide scanning range, high scanning precision, and noncontact scanning [5], so it is widely used in many fields. In underground tunnel engineering, due to the high accuracy of 3D laser scanning technology, it is used to quickly and accurately obtain diseases, such as cracks, leakage, and segment dislocation [6]. As to construction quality inspection, due to the high speed of 3D laser scanning technology, it is used to quickly obtain the 3D coordinate data of the object surface [7]. After comparing the point cloud model with the BIM design model of an object, the dimensional and position deviations generated during the construction process will show up. Olsen et al. used ground 3D laser scanning technology to analyze the deformation of concrete columns and frame structures, so the disturbance and volume change of structures can be accurately obtained, which verifies the accuracy of 3D laser scanning technology for the acquisition of structural size information [8]. Laica Scan Station P40, a kind of 3D laser scanner, is used by Liang Dong to reconstruct a 3D model of a pedestrian bridge, and the results show that the overall spatial configuration of the bridge at a certain moment can be accurately obtained through 3D laser scanning technology [9]. Xiongyao et al.

used 3D laser scanning technology to complete the point cloud data acquisition and deformation detection of a section of tunnel [10]. Yoon et al. used 3D laser scanning technology to obtain point cloud data of prefabricated bridge panels to measure component size information [11]. The study of engineering, receiving inspection, and result acquisition under 3D laser scanning technology also has been studied [12]. From the above papers, we can know that with the use of 3D laser scanning technology in different fields, the complete and precise geometric dimensions or size information of structures can be obtained and stored in the form of a massive point cloud with almost zero deviation. At present, this new measurement method has not been used to measure cable-stayed bridges' geometric dimensional information.

In this paper, 3D laser scanning technology is adopted to measure the geometric dimensions of cable-stayed bridges for the field assembly process. The main process is divided into three steps as follows: First, the point cloud data of bridges is obtained through the 3D laser scanning method. Second, the point cloud model of bridges can be obtained after the point cloud data being processed by professional processing software, the processing steps of which are divided into splicing, noise reduction, resampling, repackaging, and slice fitting. Third, using the point cloud model, each geometric dimension of bridges can be calculated conveniently and precisely. Compared with traditional measurement methods, 3D laser scanning measurement technology can achieve a comprehensive and precise grasp for the geometric dimension of bridges. A diagram of the order of the presented procedures is shown in Figure 1.

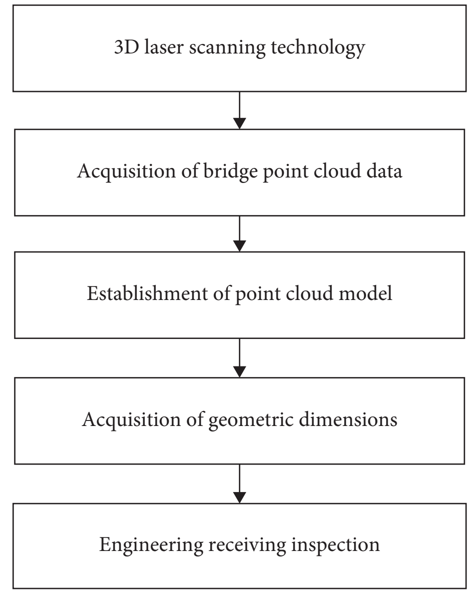

Figure 1: Diagram of the presented procedures.

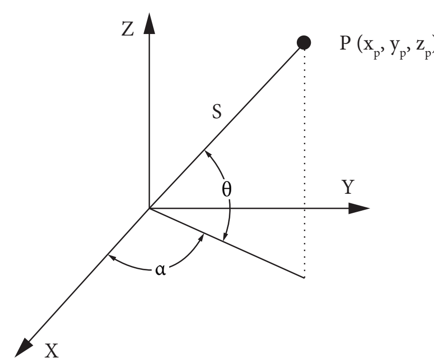

Figure 2: Principle of 3D laser scanning.

2. Methodology of 3D Laser Scanning Measurement

3D laser scanning technology uses a laser pulse transmitter inside the device to transmit laser signal to the surface of object. After arriving at the surface of object, the laser signal returns along the original path to the receiver [13–15]. Based on the time during the reflecting process and the speed of light, the distance, denoted by S, from the object to the scanner can be calculated. The horizontal angle, denoted by α, and the vertical angle, denoted by θ, from the scanner to the measured object can be obtained through the goniometric system as shown in Figure 2. So, the 3D coordinates of the target points can be calculated.

The origin of the 3D system, as shown in Figure 2, is located at the site of the laser scanner, and the direction of X and the direction of Y are used for the plane directions of the 3D system, and the direction of Z is used for the vertical direction the 3D system. The 3D coordinate of the target point $P(x_p, y_p, z_p)$ is going to be measured as follows:

$$\begin{aligned} X_p &= S \times \operatorname{Cos}\theta \times \operatorname{Cos}\alpha, \\ Y_p &= S \times \operatorname{Cos}\theta \times \operatorname{Sin}\alpha, \\ Z_p &= S \times \operatorname{Sin}\theta, \\ S &= 0.5 \times c \times t. \end{aligned} \quad (1)$$

3. Case Study of 3D Laser Scanning

In this study, a 3D laser scanner named Leica Scan Station P40, the scanning parameters of which are shown in Table 1, was used to measure the geometric dimension of a cable-stayed bridge named XingLinBao. The main process includes three steps: point cloud data acquisition, point cloud data handling, and dimension extraction, and the specific process is shown in Figure 3.

3.1. Point Cloud Data Collection

3.1.1. Set Datum Points. According to the principle of 3D laser scanning, the 3D coordinates of point cloud scanned by a single laser scanner is related to the laser scanner which is located at the origin of the 3D coordinate system, so the 3D coordinates performed by different 3D systems is mutually independent. To unify the 3D coordinates into one geodetic coordinate system, the reference datum point of the geodetic coordinate system should be arranged before scanning. This is the key work to ensure the validity of the scanning points [17]. The foundation of reference datum point should be

Table 1: Scanning parameters of Leica Scan Station P40 [16].

Parameters	Data
Distance accuracy	1.2 mm + 10 ppm
Point accuracy	3 mm@50 m; 6 mm@50 m
Target acquisition accuracy	2 mm@50 m
Noise range	0.4 mm·rms@10 m; 0.5 mm·rms@ 50 m
Scanning rate	1 million points/s
Scanning range	360° horizontally; 290° vertically

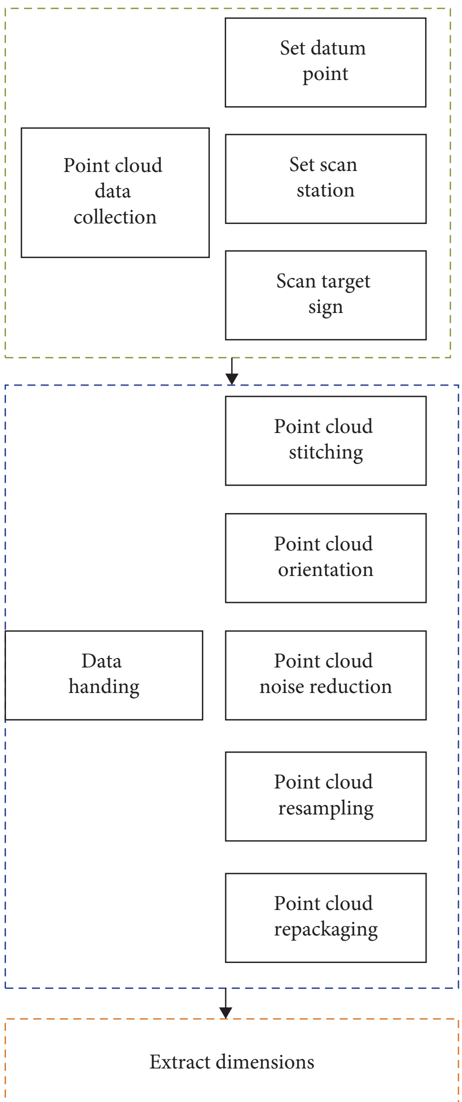

Figure 3: Process of bridge dimension measurement.

stable, free from deformation, and not easily disrupted by unpredictable environmental factors. A total of 10 reference datum points is installed on the ground, and the 3D coordinates of these referenced datum points can be obtained by GPS. Through the positional relationship between target points and reference datum points, and the positional relationship between target points and point clouds scanned from bridge components, the point cloud data of the whole bridge can be unified into the geodetic coordinate system.

3.1.2. Set Scanning Station. The basic principle of 3D laser scanning is the laser ranging. The laser scanner emits laser light and collects coordinates of 3D points reflected from the surface of the object. Therefore, the incident angle, scanning range, and scanning resolution are key parameters for point coordinate acquisition. The incident angle refers to the angle between the emission direction of the laser scanner and the normal direction of scanning target surface. The scanning range refers to the distance from the laser scanner to the surface of an object. The measurement error increases with the increase of the incident angle and scanning range. The Leica Scan Station P40 [16] has specific scanning resolution, scanning range, and incident angle parameter, so the number of the scanning station site can be determined. For some important detail parts of the object, it is necessary to increase the number of the scanning station site and the resolution of the scanner because the boundary part of object should have enough scanning point data to extract features for inverse modeling. Every site of the scanning station should be recorded and every scanning result should be checked, so that there are no scanning blind spots disrupting the scanning result.

3.1.3. Scan Target Sign. When scanning on two adjacent sites separately, the target sign of pervious station needs to be kept fixed, and the distance between the target sign and scanner should not exceed half of that between two adjacent scanning sites. Every target sign has a unique number, and at least two common target signs should be captured by every two nearest scanning, so that the point cloud data can be spliced together as a whole which is convenient for subsequent point cloud processing. It is necessary to check whether the scanned point clouds are qualified after each scanning. Qualified point clouds have features of correct scale and correct coordinates in the reference coordinate system [18].

3.2. Data Handling

3.2.1. Splice Point Cloud. Splicing point cloud is to convert point cloud data scanned from different independent coordinate systems into a unified coordinate system through the rotation matrix and translation matrix. The overall point cloud data can be obtained after point cloud splicing. There are some commonly used splicing methods including target point-based splicing, feature point-based splicing, and control point-based splicing [19]. The target point-based splicing method was adopted in this paper. For point cloud scanned from two nearest scanning stations, Cyclone software [20, 21] is used to automatically splice point cloud with two or more target points. After using the method above, the maximum splicing error of point cloud data scanned from two nearest scanning stations is 3.2 mm and the splicing error of the whole bridge is 1.5 mm. The spliced bridge

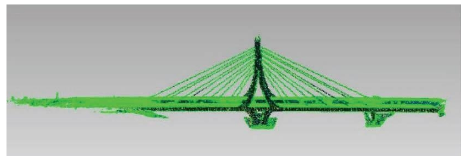

Figure 4: Point cloud splicing effect of the whole bridge.

Table 2: Point cloud data accuracy comparison.

Station names	Point cloud data rotated and translated			Point cloud data measured by GPS			Deviation		
	X'	Y'	Z'	X	Y	Z	ΔX	ΔY	ΔZ
X003	4490067.935	500063.720	1091.040	4490067.924	500063.725	1091.033	0.011	−0.005	0.007
X004	4490208.757	500074.361	1087.731	4490208.744	500074.376	1087.751	0.013	−0.015	−0.020
X007	4490090.080	499931.988	1069.945	4490090.094	499931.975	1069.967	−0.014	0.013	−0.022
X008	4490164.696	500072.404	1082.499	4490164.682	500072.416	1082.490	0.014	−0.012	0.009

Table 3: Measurement result of geometric parameters of XingLinBao bridge.

Bridge components	Items	Design value (m)	Point cloud measurement value (m)	Deviation (mm)
Main beam	Bridge length	217.000	216.988	12.0
	Bridge width	21.240	21.235	5.0
	Bridge height	2.500	2.515	15
	Cross slope	2.000%	1.75%	0.25%
Main tower	Tower height	38.000	38.008	8.0
	Verticality	0.000	0.004	4.0
	Elevation of the top of bridge tower	1136.389	1136.371	18.0

model is shown in Figure 4. Point cloud data scanned by 3D laser scanning is significantly useful in extracting geometric dimension data of bridges.

3.2.2. Point Cloud Data Orientation. After being spliced together, point cloud data can be integrated into an overall coordinate system. For elevation receiving inspection and settlement analysis, the overall coordinate system including all point cloud data should be converted into a geodetic coordinate system. The rotation matrix and translation matrix between the overall coordinate system and the geodetic system can be calculated using the parametric model [22]. The accuracy result obtained by comparing the point cloud data rotated and translated with that measured by GPS is shown in Table 2.

3.2.3. Point Cloud Noise Reduction. A laser scanner will inevitably generate noise point data in the process of data acquisition due to some unpredictable factors such as instrument error, improper manual operation, and unstable environment. Noise points are a kind of data generated by the specular reflections of reflective materials, such as glass, and are scattered and obviously far from the target object [23]. When applying such large-scale high-density point clouds, noise points may have a significant impact on 3D reconstruction and other related techniques, meaning that it will decrease the accuracy of subsequent point cloud fitting, so these must be removed. Different methods are adopted for removing different types of noise points. For some noise points which can be manually framed for deletion and for others points which are not easy to identify, they can be removed by specific function, noise points elimination, in Geomagic Studio [24, 25].

3.2.4. Point Cloud Resampling. The amount of point cloud obtained by 3D laser scanners is so large that it decreases the speed of subsequent processing such as data handling, data storing, data transmitting, and data displaying [26]. Point cloud resampling is to decrease the amount of point cloud while maintaining the feature information of the bridge. Geomagic studio has four resampling methods which are raster resampling, uniform resampling, curvature resampling, and random resampling. The random resampling method, adopted in this paper, resamples by keeping the spacing of point cloud, controls the number of point cloud in the high curvature region by keeping curvature prior, and reduces the number of point cloud while keeping the model boundary intact and shape undistorted.

3.2.5. Point Cloud Repacking. Point cloud repacking, which creates tiny triangular pieces by connecting points to fit NURBS surface, forms surface model with point cloud data. It is the foundation for preserving and extracting the dimensional data of a bridge in subsequent processing stages.

4. Bridge Geometric Dimension

The structural model of a bridge can be obtained after point cloud repacking. The steps to calculate the verticality of a bridge are shown below. Firstly, extract the bridge tower from the repacking model. Secondly, slice horizontally along the vertical direction of the bridge. Thirdly, feature fitting by using the rectangular section sliced horizontally and then extracting the coordinate of centroid from the fitted rectangular section. If there are multiple sliced rectangular sections, extracting all coordinate of centroid from each sliced rectangular section and calculating the coordinate we want by summing and averaging all centroid coordinate. Fourthly, least-squares linear fitting all centroid coordinate extracted for getting the direction vector of the fitted line [27]. Fifthly, calculating the angle, which is denoted by θ, between the direction vector of the fitted line and the unit vector, which is denoted by n (0, 0, 1), of the Z axis. So, $\tan\theta$ is calculated for showing the verticality of the bridge tower. The height of bridge tower is 38 m. To ensure the accuracy of the fitted straight line, the bridge tower was sliced along the direction of Z axis every 1 m. The maximum standard deviation from all fitting sections is 3.2 mm, and the average standard deviation from all fitting sections is 1.9 mm, so all error above is within the permitted range. The direction vector of the straight line fitted by the centroids is (0.0045, 0.0013, 0.9999). The angle between the direction of the straight line and unit vector of Z axis is 0.21° and the verticality of the direction vector is 3.66 mm, which meet the requirement of specification H/3000 mm.

Comparing the measured result with dimension data marked on construction drawings, the deviation was all less than 10 mm, and the cross slope of 1.75% was less than the design value of 2%. The geometric dimension data of a bridge named XingLinBao was measured by using the method above, and the result is shown in Table 3.

5. Conclusion

For cable-stayed bridges with large span, successful and smooth on-site installation of cable-stayed bridges is critical for construction safety. The most important prerequisite of on-site installation is the accurate geometric dimensions of components. The major contribution of this manuscript is that 3D laser scanning technology, a real scene replication technology, is adopted to measure the geometric dimensions. The whole approach can be summarized as measuring bridge's dimensions by means of 3D laser scanning. The principal processes of this approach include data handling processes for point clouds scanned by 3D laser scanning, reversing modeling based on the point clouds, and geometric dimension calculations according to the reversing modeling. Therefore, the geometric dimensions of the target bridge can be calculated accurately and conveniently.

The newly proposed method is verified based on a cable-stayed bridge named XingLinBao, and the results show that the geometric dimension deviations of components were all less than 15 mm, and the cross slope of 1.75% was less than the design value of 2% compared with dimension data marked on construction drawings. The proposed method is not limited to cable-stayed bridges, but it also is applicable to building constructions. In addition, it only measures the geometric dimensions of constructions, the materials of which are not concerned, so it is also applicable to concrete structures. In future applications, 3D laser scanning technology may be increasingly used whether in bridge engineering or other industries.

Data Availability

All the data generated or analyzed during this study are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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