Reconstruction of Ancient Stone Arch Bridge Via Terrestrial LiDAR Technology

Wei Cao 1, Yufeng Shi 1, Dong Mei1, Mingyue Li2, Dehe Liu 3

1 College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China
2 School of Foreign Studies, Nanjing Forestry University, Nanjing 210037, China
3 Jiangsu Haosen Architectural Design Co. LTD, Nanjing 210037, China

yfshi@njfu.edu.cn

Abstract. The ancient stone arch bridge is the cultural and architectural heritage of human, the protection of it is a worldwide problem. Considering the problems that some ancient stone arch bridges with a long history lack reliable design data, and it is difficult to identify their detailed geometric features efficiently, a novel reconstruction method of ancient stone arch bridge via terrestrial LiDAR scans is proposed in this paper. Firstly, the terrestrial LiDAR was applied to get the whole point clouds of the ancient stone arch bridge surface, and then the point clouds was preprocessed. The non-uniform rational B-spline (NURBS) algorithm is used to extract, fit and reconstruct the ancient stone arch bridge based on the point clouds. The results show that terrestrial LiDAR technology could be used to get point clouds of the stone arch bridge comprehensively and accurately, and realize the reconstruction of the stone arch bridge model.

1. Introduction

The ancient stone arch bridge is one of the arch bridge made of natural stone materials, and it is the cultural and architectural heritage of human, presenting the ingenuity of the ancient people and the brilliant achievements of ancient bridge construction. However, the geometry of the ancient stone arch bridge may be changed because of the long-time environmental deterioration, bridge settlement and some other factors. Besides, lack of accurate design data makes the protection of the ancient stone arch bridge becoming a worldwide problem. Therefore, it is worthwhile to doing some research on identifying the stone arch bridge overall geometric features and reconstructing the bridge accurately and efficiently.

Over the past few decades, the terrestrial LiDAR technology has been widely used in many fields, such as generating efficient and realistic 3D architectural scene model[1], health assessment of concrete structures[2]-[3], urban large-area building model[4], complex 3D geological body model[5], estimating single tree stem volume[6] and surveying some ancient tombs. What’s more, it can also be applied in the analysis of the structure of ancient stone arch bridges. A point cloud data model of the Cernadela bridge was established[7], and a series of algorithms to model the stone arch bridge via point cloud data have been researched[8]-[10].

However, all of above researches only focus on constructing the point cloud model, instead of reconstructing the realistic surface models and geometry structures of the bridge. Thus, the point clouds data collecting, preprocessing and reconstructing of an ancient stone arch bridge via Faro X330 terrestrial LiDAR scanner is proposed in this paper.
This paper is organized as follows. Section 1 elaborates the background and the significance of generating the ancient stone arch bridge. And in section 2, the work of acquisition and preprocessing of point clouds is introduced, followed by the reconstruction of the bridge in section 3. In section 4, we propose a case of the reconstruction and discuss the results. The last section concludes the work we do.

2. Preprocessing of point Clouds

The point clouds of the surface from the measured object can be acquired by means of non-contact and high-speed laser via terrestrial LiDAR scanner. The terrestrial LiDAR scanner often adopts the self-contained coordinate system, the origin of which is the laser beam emission, the starting direction of the scanning is generally the X axis and the vertical direction is generally the Z axis that the upward direction is the positive direction. Moreover, in the lateral scan plane, the Y axis and the X axis is vertical.

Influenced by the scanning range of the laser scanner, it is necessary to scan in multiple viewpoints and register the point clouds of these different positions to the same coordinate system when data acquisition is performed. The multi-viewpoint point clouds should be transformed and registered into an unified coordinate system, by which all point clouds are spliced into a complete three-dimensional space. More recently, a series of algorithms have been used to carry out the reconstruction, such as ICP iterative nearest point algorithm[11], non-rigid registration under isometric deformation[12], automatic markerless registration of point clouds with semantic-key point-based 4PCS algorithm[13], and geometric feature based splicing method[14]. In this paper, the ancient stone arch bridge is generated by using the geometric feature-based splicing method.

The scanner-space Cartesian coordinates are linked to object space via the rigid body transformation, a function of the scanner exterior orientation parameters comprising the position. The corresponding registered objective function [11] is shown as equation (1).

\[
f(R,T) = \min \sum (R p_i + T - q_j)
\]

Where, \( R \) is the point clouds rotation matrix, \( T \) is transformation matrix, \( p_i \) and \( q_j \) represent the point clouds that need to be registered respectively. \( R \) is calculated by equation (2).

\[
R = \begin{pmatrix}
\cos \alpha & \cos \beta & -\sin \gamma \\
-\cos \alpha \sin \gamma & \cos \alpha \cos \beta & \sin \alpha \sin \beta \\
\sin \alpha \sin \gamma & \cos \alpha \sin \beta & \cos \alpha \cos \beta
\end{pmatrix}
\]

Where, \( \alpha, \beta, \gamma \) are the rotation angles rolling the coordinate axis respectively.

Noisy point clouds refer to those cannot be automatically identified and removed from the object while acquiring the data. If these noisy point clouds are not removed, they would affect subsequent processing and modelling. Removing the noisy point clouds would not only reduces redundant data, but also helps to represent the realistic shape of real objects. The sampled point clouds can be represented by expression (3).

\[
P_i = g(x_i,y_i,z_i) + g'(x_i,y_i,z_i) + e_a(x_i,y_i,z_i) + e_b(x_i,y_i,z_i)
\]

Where, \( g'(x_i,y_i,z_i) \) is the deviation from its ideal value due to surface roughness, ripples and other defects in the target. \( e_a(x_i,y_i,z_i) \) is the system surveying error caused by precision, resolution of the terrestrial LiDAR scanner. \( e_b(x_i,y_i,z_i) \) is the random surveying error caused by electrical, thermal noise and other factors in the terrestrial LiDAR system[9]. The purpose of removing noisy points is to minimize the effects of the last three items in expression (3) and preserve the ideal point cloud data of the scanned objects.
To approximate the original bridge model with a small number of feature points, some methods used to simplify are proposed, such as bounding box method, random sampling method, curvature reduction method and three-dimensional grid method [15]. Among them, the random sampling method is the most used but the data sampling is uncontrollable. And the curvature reduction method simplifies the data through setting of the most advantageous spacing and curvature, aiming to reduce the number of points in the flat area and preserve the points in the curvature area where most details could be preserved. In this paper, the curvature reduction method is applied to simplify the point cloud sufficient detail to allow the work to be reproduced.

3. Methodology

The modelling of bridge refers using geometric topological information of the point clouds to construct a bridge surface approximating the original shape of the entity by fitting a series of discrete points. Several approaches to the reconstruction of real models via 3D laser scanning data have been proposed in the fields of computer vision and computer graphics over the last two decades. The non-uniform rational B-spline (NURBS) method is one of methods [3,9,10,15]. NURBS used to generate and represent curves and surfaces is a mathematical model in computer graphics and it offers great flexibility and precision in the handling of both analytic and modelled shapes. NURBS surfaces are functions of two parameters mapping to a surface in 3D space. The surface shape is determined by the control points. NURBS surfaces can represent simple geometrical shapes in compact form [15,16,17].

In this paper, the NURBS surface is adopted for surface modelling of bridge. The NURBS surface reconstruction can be represented by three kinds of equivalent expressions, namely, rational fraction, rational base function, and homogeneous coordinates [16,17].

The reconstruction of NURBS surface consists of two steps [17,18].

1. Construction of a NURBS curve. A \( k \times 1 \) NURBS curve can be described by a piecewise rational polynomial vector function defined by expression (4).

\[
P(u) = \frac{\sum_{i=0}^{n} \sum_{j=0}^m \omega_{i,j} N_{i,k}(u) d_{i,j}}{\sum_{i=0}^{n} \sum_{j=0}^m \omega_{i,j} N_{i,k}(u)}
\]

where \( \omega_{i,j} \) is weight factor, \( d_{i,j} \) is control vertex and \( N_{i,k}(u) \) is \( K \)-th order B-spline basis function.

2. Construction of a NURBS surface. A \( k \times l \) NURBS surface can be represented by a rational function defined as expression (5). Its control vertices, weight factors, and knot vector are computed by explicit formulas [15].

\[
P(u,v) = \frac{\sum_{i=0}^{n} \sum_{j=0}^m \omega_{i,j} N_{i,k}(u) N_{j,l}(v) d_{i,j}}{\sum_{i=0}^{n} \sum_{j=0}^m \omega_{i,j} N_{i,k}(u) N_{j,l}(v)}
\]

\[
U = (u_0, u_1, \ldots, u_m+k+1)
\]

\[
V = (v_0, v_1, \ldots, v_n+l+1)
\]

where the control point \( d_{i,j} \) \( (i = 0, 1, \ldots, m; j = 1,2,\ldots, n) \) presents a topological mesh which could form a control grid, and \( \omega_{i,j} \) is the corresponding weight factor. The NURBS surface is the tensor product of two NURBS curves. Hence, two independent parameter vectors \( U \) and \( V \) defined as expressions (6) and (7) respectively are used. \( N_{i,k}(u) \) and \( N_{j,l}(v) \) are the B-spline basis functions derived from Cox-de Boor recursion formula. The rational basis function is defined as expression (8).

\[
P(u,v) = \sum_{i=1}^{m} \sum_{j=1}^{l} R_{i,k;j,l}(u,v) d_{i,j}
\]

Where \( R_{i,k;j,l}(u,v) \) is a bivariate rational basis function defined by expression (9):

\[
R_{i,k;j,l}(u,v) = \frac{\omega_{i,j} N_{i,k}(u) N_{j,l}(v)}{\sum_{i=0}^{m} \sum_{j=0}^{l} \omega_{i,j} N_{i,k}(u) N_{j,l}(v)}
\]
The bivariate rational basis function $R_{i,k;j,l}(u,v)$ is the extension of the variable B-spline function, with the same function graph and geometric properties as those of the irrational B-spline function. The surface reconstruction based on the NURBS method can control and modify the shape of the curve or surface by adjusting the control vertices and weight factors, ensuring that the established model and the entity are completely consistent, and the realistic geometric structure of the scanning target is visually reproduced.

4. Experiment and Analysis

4.1. Data acquisition

The FARO’s Focus-3D terrestrial laser scanner has been used in the experiment. The 90-year-old stone arch bridge in Xuanwu Lake park at Nanjing has been chosen as the research object. The whole structure of the stone arch bridge and the measuring point layout are shown in Fig. 1.

![Figure 1. Full view of the stone arch bridge and the measuring points and target balls location](image)

Acquiring the bride’s point cloud data consists of four steps. Firstly, we develop an experimental process, followed by surveying the terrain location of the bridge. And the next goal is the layout of measure point and target ball, scanning the bridge and get the point cloud data needed lastly. During the whole experiment, six target balls are placed for 6-station scanning and the position of the target ball must be unchanged, which ensures the points that collected be complete. The point clouds that collected by the station 1, 3, 5, and 6 are used to generate the model of the bridge’s side and the bridge deck reconstruction is completed by the point cloud date from station2 and 4. The point clouds of each station at this bridge are shown in Fig. 2.

4.2. Point clouds preprocessing

After removing the noisy points, we perform the point clouds registration by the geometric feature-based splicing method described in subsection 2 and then all points would be registered one by one according to the sampling point collection sequence. In order to preserve the ideal point cloud and remove the influence of the last three errors of the sample point cloud data as much as possible, we take the sensitivity parameter as 100, limit the deviation threshold to 1mm and take 3 as the smoothness level parameter firstly. And then performing multiple experiments to determine the suitable number of iterations, helping us find that the noisy points have been effectively removed after 5 iterations of the experimental parameters according to the above values.
Figure 2. The point clouds of collected via all stations: (a) The point clouds of collected via station 1, (b) The point clouds of collected via station 2, (c) The point clouds of collected via station 3, (d) The point clouds of collected via station 4, (e) The point clouds of collected via station 5, (f) The point clouds of collected via station 6.
The point clouds simplification adopts the curvature reduction method. According to the experimental requirements, we simplify the point cloud data of the stone arch bridge with the parameter that the point cloud is 0.02mm and the curvature priority is 5. The process and final result of the preprocessing of the point clouds of the stone arch bridge are shown in Fig. 3.

4.3. Reconstruction of the bridge
A three-dimensional model of the stone arch bridge has been constructed by the preprocessed point clouds (shown in Fig. 4(c)). The NURBS surface reconstruction method is used for three-dimensional modelling and many small spatial polygons are generated according to the three-dimensional point clouds to approximate the restored solid model. The results of linear fitting and surface reconstruction of the deck are shown in Fig. 4 and the extraction and fitting results of the stone arch contour are shown in Fig. 5. In addition, on the basis of acquiring the target point clouds, the acquisition of the high-definition image of the scanning target is completed synchronously and the image coordinate synchronization is registered according to the method of subsection1. Finally, we provide the texture information to the three-dimensional model to maximize the proximity to the original body of the scanning body, as illustrated in Figure 6.
Figure 4. Reconstruction of the stone arch bridge deck: (a) The point clouds from the surface of the stone arch bridge, (b) Fitting of the bridge deck with the NURB algorithm, (c) Reconstruction of the bridge deck with NURBS surface.

Figure 5. Extraction and fitting of stone arch bridge contour
5. Conclusion
This paper introduces the process of acquiring point clouds, preprocessing and modelling method of the ancient stone arch bridge via terrestrial LiDAR technology. The reconstruction of three-dimensional model of stone arch bridge is presented based on NURBS. The results show that the high-precision and comprehensive three-dimensional geometric structure of stone arch bridge can be obtained by terrestrial laser scanning, providing reliable basic data for future monitoring and reinforcement location selection, and it is of great significance in ancient bridge restoration and landscape protection.

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