Deformation monitoring of similar material model based on point cloud feature extraction

Baoxing Zhou, Yuhui Shan, Shoufeng Yao

1Department of Civil Engineering, Shandong Jiaotong University, Jinan, People’s Republic of China
2Shandong Transportation Engineering, Consultation Company Limited, Jinan, People’s Republic of China
3Shandong Provincial Communications Planning and Design Institute, Jinan, People’s Republic of China
E-mail: zbxsfjtu@163.com

Abstract: Three-dimensional (3D) laser scanning technology can reconstruct target models and analyse structural characteristics, and extract complex geometric contents of target structures. Therefore, it is significant to apply 3D laser scanning technology to construct 3D digital models of the monitored objects and to extract their features to judge their movements. This paper presents deformation monitoring method of 3D point cloud based on image information. First, point cloud was first converted into a twodimensional intensity image. Topological relations between each point can be determined clearly through the intensity image. Second, based on the wavelet modulus maxima technology, the characteristics of two-dimensional intensity images are extracted and the corresponding feature point cloud data are obtained. Finally, According to the feature of the point cloud extracted, the change is calculated to determine the deformation of the point cloud object. An experiment was conducted by using a FOCUS3D laser scanner of FARO. The experiment results further verify that the method yields a good effect of deformation monitoring.

1 Introduction

Deformation is a common phenomenon in nature. It refers to the changes in the shape, size and position of the deformable body in time or space under various loads. From the nature of deformation, the deformation of buildings is mainly the whole (rigid body) deformation (for example: the overall translation, the overall rotation, the overall lifting, the overall tilt etc.) and the local (flexible) deformation (such as deflection, bending, cracking etc.). The task of the so-called deformation analysis is to determine the spatial and temporal characteristics of the changes in the shape, size and position of the deformable body under various loads and external forces. Deformation analysis technology based on the characteristics of the building form refers to the building or structure, parts of the shape, location, size, length, area, volume and other key geometric deformation, and the relationship between the characteristics of their internal and external deformation and to analyse the situation of the building deformation monitoring technology. Since the shape characteristic is to simplify and accurately describe the building and its structure, the change of shape feature is the description of the change of the space position of the building, and is of great significance for studying the shape deformation of the building [1, 2, 3].

Recently, 3D laser scanning has been used as a modern tool for structural inspections and condition assessments [3–5]. There are two major approaches in 3D change detection technology. Geometric comparison methods that measure 3D geometric differences and geometry spectrum analysis methods that combine geometric and spectral information for change analysis [6]. It should be noted that when the 3D geometry of the scene is relatively complex and point-to-point comparison of changes between 3D models are desired, geometric comparison approaches are the obvious choice to quantify changes at level of single point locations [7]. Prior work in this domain includes an approach for measuring bridge deflections [8], and algorithms to model beam deflections by fitting shape primitives to a deformed 3D surface [9]. Several studies have evaluated the accuracy and efficiency of modern remote sensing techniques, as a potential method for measuring bridge clearance through manipulation of dense 3D point cloud data [10–13]. The accuracy of these methods have been found comparable to that of the conventional surveying equipment (Global Navigation Satellite System or total station) with significantly lower cost and fieldwork.

In the work by [14], point-wise deviation analysis was conducted by comparing acquired point cloud data with geometric primitives such as planes or cylinders to identify seismic-induced building deformation. However, all of these methods require surface meshing, polynomial curve fitting, or assumptions about prior levels of deformation in a structure. Any of these can add error to measurements and such techniques are not readily scalable to larger and more complex structures.

This paper presents deformation monitoring method of 3D point cloud based on image information. First, point cloud was first converted into a two-dimensional intensity image. Topological relations between each point can be determined clearly through the intensity image. Second, based on the wavelet modulus maxima technology, the characteristics of two-dimensional intensity images are extracted and the corresponding feature point cloud data are obtained. Finally, according to the feature of the point cloud extracted, the change is calculated to determine the deformation of the point cloud object.

2 Methodology

2.1 Conversion of 3D point cloud into 2D intensity image

The original measurement obtained by the 3D laser scanner includes the 3D coordinates (x, y, z) of each point and the intensity information I of the target point, which reflects the scanned target reflectance to a certain extent. An intensity image is an image obtained by projecting a point cloud on 2D plane and expressing the grey value with the intensity information value. The information storage of digital image is expressed as a 2D matrix. Each element of the matrix represents the pixel value of the corresponding coordinate. Therefore, to convert the point cloud data to the corresponding intensity image, the point cloud is first meshed and the point cloud coordinate is transformed for the image coordinates, the spacing of the grid depends on the resolution of the image to be generated, the higher the resolution, the smaller the spacing, the more detail that appears.

Suppose there are N points in the point cloud data, to generate an intensity image with a projection surface of XOY, a width of W and a height of H.
According to the following formulas (3) and (4), the corresponding coordinates of \((X_i, Y_i, Z_i)\) in point cloud are \((X'_i, Y'_i)\) in its intensity image

\[
X'_i = \frac{(X_i - X_{\text{min}}) \times W}{X_{\text{max}} - X_{\text{min}}} ,
\]

\[
Y'_i = \frac{(Y_i - Y_{\text{min}}) \times H}{Y_{\text{max}} - Y_{\text{min}}} .
\]

After the image coordinate being calculated, the grey value of the pixel in the image is set as the intensity value of the corresponding point cloud coordinate \((X_i, Y_i, Z_i)\). If there are multiple point cloud coordinates mapped to the same pixel coordinate, the grey value takes the maximum intensity of each point. Since the point cloud is a collection of discrete points, when generating an intensity image, part of the pixels of the image do not have a point cloud correspondence, and the grey value can be given by performing an average interpolation of eight neighbours on the pixel.

### 2.2 Feature extraction based on wavelet modulus maxima

Image feature extraction refers to the process of extracting pixels or other pixels of interest in the image that reflect features such as solid shapes and textures. Building structure line features refer to the shape of an entity such as edges, outlines, lines etc. The most important features for point clouds are curves and surfaces, since the ultimate goal of 3D modelling based on laser point clouds is to represent the solid model through a series of curves and surfaces.

A big advantage of wavelet transform is that it has good local characteristics both in time and frequency domain. Since the edge information is corresponding to the local mutation of some or other pixels of interest in the image that reflect features such as the shape of an entity such as edges, outlines, lines etc. The most advantages. Edge detection based on wavelet modulus maximum principle can be described as follows:

Define a 2D smooth function \(\theta(x, y)\) that satisfies the following formula:

\[
\int \int \theta(x, y) dx \, dy = 1 .
\]

It quickly attenuates to zero at infinity. Using this smoothing function to find the partial derivatives of \(x\) and \(y\), respectively. The wavelet function can be obtained, that is

\[
\psi'(x, y) = \frac{\partial \theta(x, y)}{\partial x} \quad \psi''(x, y) = \frac{\partial \theta(x, y)}{\partial y} .
\]

Introduction of a mark

\[
\tau_i(x, y) = \frac{1}{s} \begin{pmatrix} x \\ y \\ z \end{pmatrix} .
\]

In this case, wavelet transform is applied to the 2D image signal \(f(x, y)\)

\[
W(f(x, y)) = f(x, y) * \psi(x, y) ,
\]

\[
W''(x, y) = f(x, y) * \psi''(x, y) .
\]

In the formula: \(s\) is the scale of the wavelet transform; * is a convolution operation. Written in matrix form:

\[
W_e(x, y) = \sum \frac{\partial f(x, y)}{\partial x},
\]

\[
W''_e(x, y) = \sum \frac{\partial f(x, y)}{\partial y} .
\]

From the formula (8), we can see that the two components after wavelet transform are, respectively, proportional to the two components of the gradient vector after the smoothing function of the image is smoothed. The edge point is actually the inflection point of the surface \((f + 2\theta)(x, y)\), which is the maximum or minimum value of the first derivative. Therefore, the edge detection of the image is to find the local maximum point of the gradient vector mode on the \(s\) scale. The local maxima of wavelet transform at \(s\) scale is defined as:

\[
M_e(x, y) = \sqrt{\left| W(x, y) \right|^2 + \left| W''(x, y) \right|^2} .
\]

where \(\sqrt{\cdot}\) is a positive square root operation. By discretising (8) and (9), 2D discrete wavelet transform can be obtained. Applying it to discrete digital image, calculating the local maxima of the wavelet transform module, and selecting the appropriate segmentation method, the edge contour of the image can be detected.

### 2.3 Image features are mapped to point cloud features

The feature line extracted from the point cloud intensity image is composed of a series of image pixels, and corresponding points have corresponding points in the point cloud. After the point cloud intensity image is generated, the correspondence between the point cloud coordinates \((X_i, Y_i, Z_i)\) and the coordinates \((X'_i, Y'_i)\) of the points in the intensity image is generated. Therefore, the corresponding set of points in the image can be obtained. These points make up the corresponding features in the point cloud. However, due to the projection disparity, these points do not necessarily reflect the characteristics of the point cloud. These points are need to be simulated in order to eliminate the impact of noise points and improve the accuracy of feature extraction.

### 3 Experiment and results

#### 3.1 Design of observation scheme

According to the ratio of 1: 200, a model of mining subsidence similar material was made. The model is 2 m long and 1.6 m high. When the model is mined, strip mining is carried out in the following order: the lower coal seam is first mined and the upper coal seam is mined after a few days Strip Mining, simulating multiple Coal Seam Strip Mining. According to the location of the model, a scanning observation point is established at a distance of 8 m from the centre of the model, and repeated scanning is performed on each monitoring point laid on the model.

#### 3.2 Model monitoring point layout

In the model, circular marks with an inner diameter of 1 cm and an outer diameter of 2 cm are laid as monitoring points. According to the rule of surface subsidence, combined with the layout experience of observation points on the ground, a total of ten observation lines are laid out on the model. The first observation line is laid on the surface of the model to monitor the change of the ground surface. The second to the fifth observation line 5 cm apart, the distance between the sixth to the tenth observation line is 10 cm, which is used to monitor the change of rock movement. 21 monitoring points (round marks) are laid on each measuring line, with the distance between the measuring points being 10 cm. The monitoring points are distributed as shown in Fig. 1.

#### 3.3 Data analysis

In order to obtain the deformation information of the model, the point cloud data are processed and analysed, which is mainly divided into three steps: First, the two-dimensional intensity image
of the point cloud data is obtained according to the reflection intensity information of the point cloud. Second, using the wavelet algorithm based on modulus maxima to extract the features of the monitoring points, the point cloud data of the monitoring points are obtained. Third, point cloud data fitting, according to point cloud data monitoring point fitting to get the coordinates of the centre of the monitoring point.

i. **Point cloud intensity image acquisition:** According to the method described in this article, the monitored point cloud data is converted into corresponding 2D intensity images. This paper chooses four monitoring data of different excavation stages as the research object, as shown in Fig. 2.

ii. **Monitoring point feature extraction:** The wavelet transform feature extraction technique based on module maximum is applied to 2D intensity image of the monitoring object of similar material test to extract point cloud data of monitoring points of each scanning measurement. The feature extraction results are shown in Fig. 3.

iii. **Three-dimensional fitting data analysis:** Using the least square fitting principle, the extracted point cloud data are fitted to obtain the 3D coordinates of the centre of the monitoring point. Subtracting the fitting data of each scan from the data of the first fitting, the settlement deformation and the horizontal displacement curve of each monitoring point are obtained. Fig. 4a is the displacement curve of the fourth monitoring point in the X-direction, Fig. 4b is the displacement curve of the fourth monitoring point in the Y-direction, and Fig. 4c is the displacement curve of the fourth monitoring point in the Z-direction. The deformation of each monitoring point is basically in line with the displacement variation law of multiple coal seam mining in the mining subsidence. The maximum sinking amount of the model surface measuring point is \( \sim 1 \) cm, and the maximum sinking amount of the lower monitoring point is \( \sim 6 \) cm.

The maximum subsidence of the lower monitoring point is greater than the maximum subsidence value of the surface because the measuring point of the lower rock formation is closer to the coal seam. During mining, the lower rock formation of the goaf occurred collapse, so the measuring point reflects the sinking larger.

4 **Conclusion**

In this paper, aiming at the characteristics of 3D laser scanning measurement, the similar material deformation monitoring method based on point cloud data is studied. The main conclusions are as follows:

i. Using the characteristics of point cloud data including colour and reflection intensity information, the wavelet transform modulus maximum technique is introduced into the feature extraction of point cloud intensity image, and the extraction of irregular curve features based on point cloud intensity image is proposed. Applying it to deformation simulation of similar materials verified the feasibility of the method.
Ground 3D laser scanning technology and the traditional observation methods are significantly different; it can reproduce the entire process of dynamic changes of 3D model, and feature extraction can be carried out at any time. It can also provide the possibility for the inversion analysis of surface measured data and can provide a new and more effective method for research on the law of dynamic subsidence.

In addition, the advantages of 3D point-and-point displacement observation using 3D laser scanning technology are simplicity, high efficiency and precision, without complicated observation, recording and calculation.

5 Funding

This work was financially supported by A Project of the Key Research and Development Program of Shandong Province (2019GGX101045), Shandong Province Higher Educational Science and Technology Program (J14LG07), Doctoral research fund of Shandong Jiaotong University.

6 References

[1] Fathi, H., Dai, F., Lourakis, M.: ‘Automated as-built 3D reconstruction of civil infrastructure using computer vision: achievements, opportunities, and challenges’, Adv. Eng. Infor., 2015, 29, (2), pp. 149–161
[2] Khaloo, A., Lattanzi, D.: ‘Hierarchical dense structure-from-motion reconstructions for infrastructure condition assessment’, J. Comput. Civ. Eng., 2015, 30, (2), pp. 04015015:1–04015015:14
[3] Zhou, Z., Gong, J., Guo, M.: ‘Image-based 3D reconstruction for posthurricane residential building damage assessment’, J. Comput. Civ. Eng., 2016, 30, (2), pp. 040–015
[4] Ghasremani, K., Khaloo, A., Lattanzi, D.: ‘Automated 3D image-based section loss detection for finite element model updating’. 33rd Int. Symp. on Automation and Robotics in Construction, Auburn, AL, USA, August 2016, pp. 411–419
[5] Mukupa, W., Roberts, G.W., Hancock, C.M., et al.: ‘A review of the use of terrestrial laser scanning applications for change detection and deformation monitoring of structures’, Surv. Rev., 2017, 49, (353), pp. 99–116
[6] Qin, R., Tian, J., Reinhartz, P.: ‘3D change detection approaches and applications’, ISPRS J. Photogramm. Remote Sens., 2016, 122, pp. 41–56
[7] Lindenbergh, R., Pietrzyk, P.: ‘Change detection and deformation analysis using static and mobile laser scanning’, Appl. Geomat., 2015, 7, (2), pp. 65–74
[8] Fuchs, P., Wash, G., Chase, S., et al.: ‘Applications of laser-based instrumentation for highway bridges’, J. Bridge Eng., 2004, 9, (6), pp. 541–549
[9] Cabaleiro, M., Riveiro, B., Arias, P., et al.: ‘Algorithm for beam deformation modeling from LiDAR data’, Measurement, 2015, 76, pp. 20–31
[10] Liu, W., Chen, S.: ‘Reliability analysis of bridge evaluations based on 3D light detection and ranging data’, Struct. Control Health Monit., 2013, 20, (12), pp. 1397–1409

[11] Truong-Hong, L., Laefer, D.F.: ‘Using terrestrial laser scanning for dynamic bridge deflection measurement’. IABSE Istanbul Bridge Conf., Istanbul, Turkey, August 2014, pp. 11–13

[12] Park, H.S., Lee, H.M., Adeli, H., et al.: ‘A new approach for health monitoring of structures: terrestrial laser scanning’, Comput.-Aided Civ. Infrastruct. Eng., 2007, 22, (1), pp. 19–30

[13] Lindenbergh, R., Pfeifer, N.: ‘A statistical deformation analysis of two epochs of terrestrial laser data of a lock’. Proc. of the 7th Conf. on Optical, Vienna, Austria, October 2005, pp. 61–70

[14] Pesci, A., Tezza, G., Botti, E., et al.: ‘A laser scanning-based method for fast estimation of seismic-induced building deformations’, ISPRS J. Photogramm. Remote Sens., 2013, 79, pp. 185–198