KEY WORDS  laser range scanner; volume measurement; 3D rebuilding

ABSTRACT  In this paper the development of the technology of the laser scanning is summarized. The principles of laser range scanning are introduced. Based on the laser scanning technology and methods, which are investigated by the authors to survey deposit volume, a surveying system is developed and a practical application is performed. It is shown that the laser-scanning technology has obvious advantages such as measurement precision, automation and visualization of observed data in comparison with the traditional methods. As a result, labor intensity is relieved obviously and work efficiency is promoted.

1 Introduction

In recent years laser range scanner, which is one representative of the high and new technology industries, has been making great progress in real-time acquisition of multi-level of 3D spatial object. Airborne system, combined with other positioning technology such as GPS, INS, and remote sensing, could be applied in real-time and high precision data acquisition for large area Digital Surface Model (DSM). Besides, this system may partly penetrate tree canopies to get directly real terrain 3D spatial information that cannot be acquired in traditional photogrammetry. Terrain moving system or car-based system can be applied to monitoring and modeling 3D spatial complex objects such as railway, highway, tunnels and large buildings. It is one of the most important technologies that should be resolved in building 3D city GIS. Pint-sized fixed system can realize the 3D measurement of body and kinds of mould, and the management of industrial automatic production line. Integrated with virtual reality and other technology, 3D real-time monitoring of flood, earthquake and environment in large area will be performed in the future. Furthermore, it can be applied to the speedy measurement of engineering excavation and deposit volume, management of intellectualized traffic system (ITS), urban development investigation and urban planning, measurement and research on medicine, real-time automatic control in industrial product line and so on.

Currently lots of international corporations and research institutes have devoted a great deal of manpower and material resources to correlative technology research and system development. In Canada, Calgary University developed an airborne laserscanning system, which integrated laser scanner with GPS and data communication equipment, to realize 3D data acquisition and took perfect effect in 1998. In the Netherlands, the Survey Department of Rijkswaterstaat has been investigating the feasibility of extracting topographic information from laser measurement since 1988\(^1\). The University of Tokyo of Japan integrated 2D laser scanning system with other sensors and experimented in
1999[2, 3]. Some of universities and research institutes in America, France and Hong Kong are doing some researches on laser range scanning.

According to mounted platform, laser-scanning technology can be divided into airborne laser-scanning and ground-based laser scanning. A few commercial companies have offered their airborne and/or ground-based surveying systems. Airborne laser scanning system is mainly applied to the acquisition of large area topographic data[4-8]. For instance, TopEye system is developed in Sweden, ALTM1020GG system by Optech Corporation of Canada, Fli-Map1 system in America, and so on.

Ground-based laser scanner, which is mainly used in the reconstruction of 3D city and acquisition of local region geographic information[2, 3, 9, 10], has an important function in rebuilding 3D spatial object and absorbs more and more attentions. Cyrax System developed by Cyra Technologies Inc. of America is a typical 3D ground-based laser-scanning system. Moreover, SICK Optic-Electronic Co. Ltd. and IBEK Lasertechnik GmbH of Germany have rather mature industrial production respectively. In a word, airborne system is getting more and more mature in production and application. While that of ground-based system is in developing stage.

2 Principles of laser scanning

Laser-scanning surveying gets the surface shape of objects through laser scanners and range sensors. Commonly laser scanner is composed of laser transmitter, laser receiver, time-counter and microcomputer. The laser transmitter drives a laser diode to send laser pulses periodically. The receiving lens, after accepting the back-reflected signal from the object surface, produces a receiving signal. A steady quartz clock counts the time difference between emission and reception. After this, the observation data is processed, displayed and stored by using the microcomputer. As a result the distances and angles are available for matching with the data acquired by range sensor. After processing with the corresponding system software, 3D coordinate data of the object can be acquired. And kinds of measurement and modeling can be established.

In the airborne system, the laser-scanning surveying system, which acquires 3D-ground information, is integrated with DGPS, which realizes dynamic positioning, INS, which determines the stature parameters, and CCD camera, which captures the surface image. In the ground-based system, Y₀ and Z₀ (Z₀ is the distance between scanner center and reference horizontal surface), the value of the angle parameters of the exterior orientation elements, are constants when the laser scanning surveying system is mounted onto the fixed platform. While X₀, s and θ are variables. These constants can be calibrated in lab when the system is installed and integrated or be determined only one time by setting control points on the spot. Thus the survey and calculation process can be simplified. Fig. 1 shows the working principles and the laser scanning surveying coordinate system.

![Fig. 1 Sketch map of laser-scanning surveying system](image)

2.1 Geometric model and precision analysis

As to linear scanning, we take the progressive direction as the X-axis. The Z-axis coincides with the zenith direction. And the scanner projection center is taken as the origin of the object space coordinate system. X-axis, Y-axis and Z-axis form a right-hand coordinate system (shown in Fig. 1). In this coordinate system, the exterior orientation elements are (X₀, Y₀, Z₀, ϕ, ω, κ). Laser scanner measures the distances between scanner and object surface. The angle θ between the direction of laser pulse and Z-axis is determined by the encoder. The coordinate of the X-axis direction is determined by range sensors. For each pulse, there are x = 0, y = -s·sinθ, z = -s·cosθ. The space coordinates of footprints can be computed by the collinear equa-
tion in photogrammetry and expressed as follows:

$$\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
X_0 \\
Y_0 \\
Z_0
\end{bmatrix} + \begin{bmatrix}
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_2 \\
c_1 & c_2 & c_3
\end{bmatrix} \begin{bmatrix}
0 \\
s \cdot \sin \theta \\
s \cdot \cos \theta
\end{bmatrix}$$

(1)

Where $a_1 = \cos \varphi \cos \kappa - \sin \varphi \sin \kappa \cos \omega$; $a_2 = - \cos \varphi \sin \kappa \cos \omega$; $a_3 = - \sin \varphi \cos \kappa$; $b_1 = \cos \omega \sin \kappa$; $b_2 = \cos \omega \cos \kappa$; $b_3 = - \sin \omega$; $c_1 = \sin \varphi \cos \omega + \cos \varphi \sin \omega \sin \kappa$; $c_2 = - \sin \varphi \sin \omega + \cos \varphi \cos \omega \sin \kappa$; $c_3 = \cos \omega \cos \varphi$.

Supposing that observation values $(X_0, Y_0, Z_0, \varphi, \omega, \kappa, s, \theta)$ are independent mutually, and differentiating Eq. (1) we can obtain the estimation formula as follows:

$$m_X = a_1 m_{X_0} + a_2 m_{Y_0} + a_3 m_{Z_0} + a_4 m_\kappa + a_5 m_\omega + a_6 m_\varphi$$

$$m_Y = a_7 m_{X_0} + a_8 m_{Y_0} + a_9 m_{Z_0} + a_{10} m_\kappa + a_{11} m_\omega + a_{12} m_\varphi$$

$$m_Z = a_{13} m_{X_0} + a_{14} m_{Y_0} + a_{15} m_{Z_0} + a_{16} m_\kappa + a_{17} m_\omega + a_{18} m_\varphi$$

Where $m_X$, $m_Y$, $m_Z$ express the orientation root mean square errors of $X$-axis, $Y$-axis and $Z$-axis. We have:

$a_{11} = a_{22} = a_{33} = 1$;

$a_{12} = a_{13} = a_{21} = a_{23} = a_{32} = a_{31} = a_{24} = a_{34} = 0$;

$a_{14} = - s \{ (\sin \varphi \sin \kappa - \cos \varphi \sin \omega \cos \kappa) \sin \theta - \cos \varphi \cos \kappa \sin \omega \}$;

$a_{15} = - s \{ (- \sin \varphi \cos \omega \cos \kappa) \sin \theta + \sin \varphi \cos \omega \sin \kappa \}$;

$a_{16} = s \{ (\cos \varphi \cos \kappa - \sin \varphi \sin \omega \cos \kappa) \sin \theta \}$;

$a_{17} = \frac{1}{s} \{ (\cos \varphi \sin \kappa + \sin \varphi \sin \omega \cos \kappa) \sin \theta + \sin \varphi \cos \omega \cos \kappa \}$;

$a_{18} = s \{ (\cos \varphi \cos \kappa + \sin \varphi \sin \omega \cos \kappa) \cos \theta - \sin \varphi \cos \omega \sin \kappa \}$;

$a_{25} = s \{ \sin \varphi \cos \kappa \sin \theta + \cos \varphi \cos \omega \cos \theta \}$;

$a_{26} = \cos \omega \cos \varphi \sin \kappa$;

$a_{27} = - (\cos \omega \cos \kappa \sin \theta - \sin \omega \cos \varphi \cos \theta)$;

$a_{28} = - s \{ \cos \varphi \cos \omega \cos \varphi \sin \kappa \}$;

$a_{35} = - s \{ (\cos \varphi \cos \kappa \cos \theta - \sin \varphi \sin \omega \sin \kappa) \}$;

$a_{36} = s \{ (\sin \varphi \cos \omega + \cos \varphi \sin \kappa \sin \omega) \sin \theta \}$;

$a_{37} = \frac{1}{s} \{ (\sin \varphi \sin \kappa + \cos \varphi \sin \omega \cos \kappa) \sin \theta - \cos \varphi \cos \kappa \cos \omega \}$

Assume that a certain profile has $n$ data points. Firstly according to the different measurement environment, different parameter value $j$ is selected (generally $j$ is from 2 to 5, $j < i$) when point $S_i((n-2) > i > 2)$ is filtered. Secondly, the distances from $S_i$ and the adjoining $j$ points $S_{i-j}, S_{i-j+1}, \ldots, S_{i-1}, S_i, S_{i+1}, \ldots, S_{i+j}$ in each adjacent side to $S_0$, which mark as $D_{i-j}, D_{i-j+1}, \ldots, D_{i-2}, D_{i+1}, \ldots, D_{i+j}$.
\[ f_d = \left\lfloor D_i - \frac{\left( \sum_{k=i+1}^{i+j} D_k + \sum_{k=i+1}^{i-j} D_k + 2 \cdot j \cdot D_i \right)}{4j} \right\rfloor > f \] (3)

If the point \( D_i \) can meet Eq. (3), it will be filtered. When \( S_i \) is located on the boundary (\( 0 < i < 2 \) or \( n - 2 < i < n \)), the adjacent points to the right or left side of \( S_i \) are chosen and the processing is similar.

2) Calculation of deposit volume

After data filtering, terrain irregular network (TIN) can be constructed and the digital elevation model (DEM) are generated. According to DEM, the calculation of the deposit and 3D visualization can be performed.

It is convenient to obtain profile map from DEM at any orientation, which is expressed by the terrain height \( Z_i \) with interval \( \Delta T_{ik} \) as Fig. 3 shows. The area of the profile can be acquired from Eq. (4).

\[ F = \frac{Z_1 + Z_2 + Z_3 \Delta T_{12} + Z_2 + Z_3 \Delta T_{23} + \ldots + Z_{n-1} + Z_n \Delta T_{n-1,n}}{2} \] (4)

For the mutual parallel profiles whose span is \( \Delta S_{ik} \), the volume can be calculated according to the following equation.

\[ V = \frac{F_1 + F_2 + F_3 + F_4 + F_5 + \ldots + F_{m-1} + F_m + F_{m+1}}{2} \Delta S_{12} + \Delta S_{23} + \ldots + \Delta S_{m-1,m} \] (5)

The precision is:

\[ \sigma_V = \frac{\Delta S_{12}^2 \sigma_F^2}{4} + \frac{(\Delta S_{12} + \Delta S_{23})^2}{4} \sigma_F^2 + \ldots + \frac{\Delta S_{m-1,m}^2}{4} \sigma_F^2 \] (6)

When the profile intervals \( \Delta S_{ik} \) are equal to \( \Delta q \), and the distances \( \Delta P \) between the points in the profile are also equal, the volume precision is:

\[ \sigma_V = \sqrt{\left( \frac{n - \frac{3}{2}}{2} \right) \left( m - \frac{3}{2} \right) \Delta P \cdot \Delta q} \sigma_z \] (7)

where \( \sigma_z \) is the altitude precision of the profile point after interpolation.

3 Laser range scanning system

We have succeeded in developing a laser range scanning system, which is called LD-1, for practical application. The system is composed of hardware segment and software segment.

1) The hardware segment includes 2D laser scanner, velocity sensor, microcomputer, and data communication equipment. The structure of the system is shown as follows:

The laser scanner is connected with industrial computer through ISA line to realize the real-time transmission of the data. The velocity sensor transmits the data to the industrial computer through standard interface RS232. And the computer can complete the data record, memory, processing and output.

2) The software segment includes data acquisition, data communication, data processing, 3D reconstruction and visualization, and the output of the result.

LD-1 laser range scanning system can realize the automation from initial data collection to the form of the report chart. It mainly includes five modules as follows:

(1) Engineering Management Module. It realizes the engineering management of laser surveying.

(2) Data Acquisition Module. In this module initial data of the surveying can be acquired in real-time. The
module includes the storage of the initial data and the communication between computer and other correlative sensors such as laser scanners.

(3) Data Processing Module. The module, which is the core of the system, realizes the main functions of the system including data preprocessing, 3D coordinate calculation, volume evaluation, and volume variance comparison.

(4) 3D Display Module. This module provides the client with the real-time rebuilding of the scene. It includes the data input, model construction, 3D display and 3D operation.

(5) Output Module. The module, which makes the output of the system, provides the client with the output in the form of report chart. The main contents include current volume, volume variance, output of the volume report chart, and generation of statistic chart.

4 Laser scanning system application

Laser scanning system has succeeded in Xin'gou Power-generating Plant located in Wuhan, Hubei province. There was a dry coal shed and an outdoor coal-stack. Beside the outdoor coal-stack there was a coal-discharged equipment and its railway. While in the dry coal shed there was a travelling crane and its rails. The size of the dry coal-shed was 62 m x 24 m. We measured the volume of the coal-stack in the dry coal shed with the laser scanning system. The system platform mounted on the travelling crane that could run along the stationary rails. With the movement of the travelling crane, the system scanned the coal-stack continuously.

4.1 Application

The laser scanning system is fixed on the travelling crane. The relative coordinate system is adopted. In this coordinate system the center of the laser scanner is taken as the origin of the system. We take the forward direction as X-axis and Z-axis coincides with the vertically downward direction. X-axis, Y-axis and Z-axis form the right-hand coordinate system. The whole field operation including repeated scanning can be accomplished within two minutes. There are about 190,000 effective points that have a ten centimeters interval after data post-processing. The relative precision of the volume calculated by repeated scanning is within 5%, which is shown in Table 1.

The surveying error results from many factors. For example, the travelling crane and the rail are not horizontal or parallel. And it is also because of the fluctuation and the uneven velocity of the travelling crane during the course of the advance, the range error of the scanner, the error of boundary extracting, and the approximate error that resulted from the simulated surface based on sampling the true surface. In practice, we can take several times of measurements, and compare the relative error of the data to evaluate the surveying precision.

4.2 Reconstruction

After the 3D spatial data are acquired the 3D coal-stack model is formed in the form of DSM. With OpenGL 3D model is displayed and data reliability is detected. Fig. 5 shows the 3D digital surface model of the coal-stack by using computer. The rebuilding result verifies that the collection of the initial data is reliable, the calculating method is correct, and the algorithm is feasible.

Table 1 Data statistic tablet

| Scanning sequence | Valid points | Volume/m³ | Reserve/t | Relative precision |
|-------------------|--------------|-----------|-----------|-------------------|
| 1                 | 196 804      | 6 814     | 7 495     | 3.3%              |
| 2                 | 199 206      | 6 792     | 7 471     |                   |

Note: the density of the coal takes 1.1t/m³.

5 Conclusion

The application shows that the deposit volume moni-
toring using laserscanning system is a new efficient method with high precision. It has the superiority that can not be replaced by traditional surveying method.

1) High speed. Even in large-scale coal-stack, the field operations can be finished within ten minutes.

2) High automation and low labor intensity. Computer processes all of the data collected in the field operations automatically. It needs only one or two persons to finish the whole work and show the final results.

3) High precision. Data acquired by laser scanner have the characteristics of high density and enormous volumes that can describe the surface character of the coal-stack entirely. Just so the volume of the coal-stack can be calculated with high precision. Laser scanning system resolves the surface approximate error that can not be easily resolved by traditional method.

4) Broad prospect. The system can be used widely to all kinds of deposit volume surveying. And it has broad prospect in electric power, coal, steel and engineering construction and so on.

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