# Discussion on the characteristics of the TLS point cloud measured in circular tunnel

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## 1. Introduction

Terrestrial laser scanning (TLS) is gradually applied in tunnel 3D model reconstruction and deformation monitoring. [1] The accuracy of the spatial location of point clouds measured by TLS is essential for tunnel 3D modeling, and the point cloud distribution is a basis for tunnel 3D modeling and designing inspection schemes. However, the characteristics of point cloud in a tunnel have not been studied clearly. In this paper, a generative model of point cloud distribution is constructed, and a characterization method of point cloud distribution is proposed.

## 2. Generation mode of the point cloud in a circular tunnel

The physical model of the TLS scanning tunnel is constructed using the laser scanning process, as shown in Fig. 1. The TLS rotates in both vertical and horizontal planes when emitting a laser outward (see Fig. 1(a) ). When the tunnel is assumed to be a circular cylinder shape, the coordinate of the sampling point in the fourth quadrant are expressed in Eq. (1). Part of the sampling points on the tunnel lining is shown in Fig. 2(b). The sampling points overlap at the upper and lower vertices of their trajectory curves and is staggered at their nonvertex points in space. The density of the point cloud distribution shows a non-uniform variation.

$$x_i = \frac{R\cos H_i \tan H_i}{\sqrt{\cos^2 H_i + \tan^2 V_i}},\ y_i = \frac{R\cos H_i}{\sqrt{\cos^2 H_i + \tan^2 V_i}},\ z_i = \frac{R\tan V_i}{\sqrt{\cos^2 H_i + \tan^2 V_i}} \qquad (1)$$

for $i = 1,2,\dots,n$, where $y_i^2 + z_i^2 = R^2$, $\tan H_i = \frac{x_i}{y_i}$ , and $\tan V_i = \frac{z_i}{\sqrt{x_i^2+y_i^2}}$.

The accuracy of individual point measurements in the point cloud is affected by the TLS mechanism, atmospheric conditions, object surface properties, and scan geometry. [2] The measured distance from the TLS center to the observed point is elongated or shortened along the laser incidence direction, as shown in Fig. 1(c). It makes the observed points not fit the measured surface completely. The undulating value of the sampling points in the same ring caused by considering only the TLS linearity error are called range error $\Delta r$. $\Delta r$ is expressed in Eq. (2).

$$\Delta r = 2a + 2b * \sqrt{x_i^2 + y_i^2 + z_i^2}, \quad (2)$$

where $a$ and $b$ are a factor of TLS linearity error.

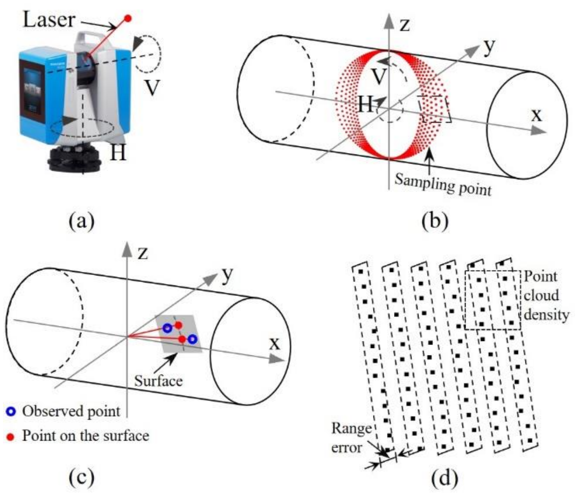


Fig. 1 Point cloud generation mode.

In summary, the TLS rotation pattern and tunnel geometry regulate the density of point cloud distribution. Moreover, measured errors caused by various factors, such as the TLS mechanism, make the point cloud not fit the measured surface completely. Fig. 1(d) shows an area of point cloud distribution with its density and the range error. The effects of density and range error on the point cloud distribution are described in the next section.

## 3. Characterization method of point cloud distribution

The density of the point cloud distribution can be expressed by the point cloud spacing. The sampling point trajectory generated by a vertical rotation of TLS is designated as a ring. Fig. 2(a) shows the sampling points within the adjacent rings. The spacing of adjacent sampling points within the same ring is called the point spacing $d_{\text{point}}$. The spacing between adjacent rings is called the ring spacing $d_{\text{ring}}$. The angle between the line of adjacent points in the ring and the horizontal plane is denoted as the inclination angle $\alpha$. According to Helen's formula, $d_{\text{point}}$, $d_{\text{ring}}$, and $\alpha$ with the coordinate of sampling points are expressed in Eq. (3).

$$d_{\text{point}} = P_0P_1 = \sqrt{(x_1-x_0)^2+(y_1-y_0)^2+(z_1-z_0)^2},\ d_{\text{ring}} = \frac{2S}{d_{\text{point}}},\ \alpha = sin^{-1}\frac{d_{\text{ring}}}{P_0P_2}, \tag{3}$$

where $S=\sqrt{p(p-P_0P_1)(p-P_0P_2)(p-P_1P_2)}$, $p=\frac{P_0P_1+P_0P_2+P_1P_2}{2}$, $P_0P_1=\sqrt{(x_1-x_0)^2+(y_1-y_0)^2+(z_1-z_0)^2}$, $P_0P_2=\sqrt{(x_2-x_0)^2+(y_2-y_0)^2+(z_2-z_0)^2}$, $P_1P_2=\sqrt{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2}$.

Fig. 2(b) shows that the point cloud exhibits a thickness normal to the measured surface due to range error $\Delta r$. This thickness is called the point cloud thickness $h$ in this study. According to the geometric relationship, $h$ of a section of sampling points in the same ring is expressed as Eq. (4).

$$h = \frac{2y_i\left(a+b*\sqrt{x_i^2+y_i^2+z_i^2}\right)}{\sqrt{x_i^2+y_i^2}}, \tag{4}$$

where $h=\Delta r\cos H_i$, $H_i=\cos^{-1}\frac{y_i}{\sqrt{x_i^2+y_i^2}}$.

For a testification calculation model, R and Z are assumed as 4.1 m and 0.3 m, respectively. Horizontal and vertical angular resolution is 0.016 °, and linearity error is 1 mm + 10 ppm/m in TLS. Fig. 2(c) and Fig. 2(d) show the trends of the parameters regarding the point cloud distribution with tunnel length $x_i$, respectively. $d_{\text{point}}$ and $d_{\text{ring}}$ increase with an increase in $x_i$; however, the growth rate of $d_{\text{ring}}$ is larger. $\Delta r$ slowly increases with increase in $x_i$. $h$ decreases with an increase in $x_i$, and the rate of decrease becomes smaller. The variation of the above parameters with $x_i$ quantifies point cloud distribution. These parameters can be used as indicators to describe the point cloud distribution.

In summary, point cloud spacing, including point spacing $d_{\text{point}}$ and ring spacing $d_{\text{ring}}$, can quantitatively calculate the density of point cloud distribution and describe the point cloud trajectory. Point cloud thickness, adjusted by range error and incidence angle, can quantify the undulation of the point cloud on the measured surface and reflect the measurement error.

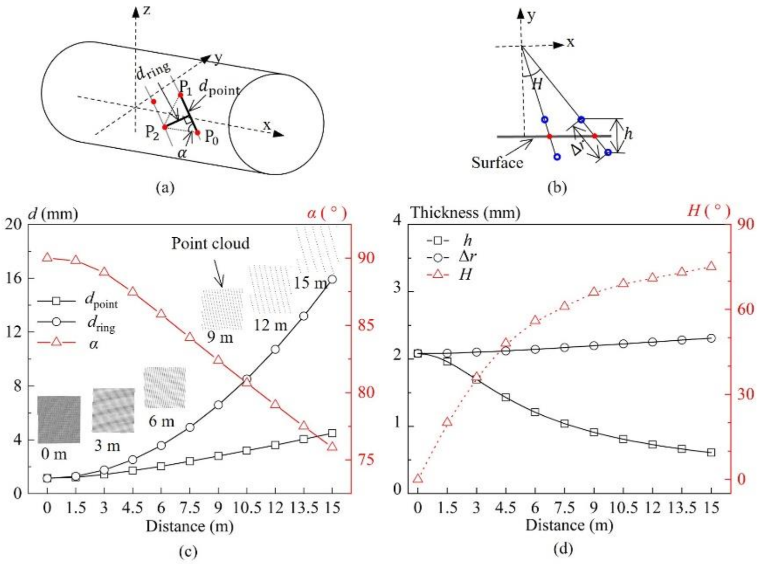


Fig. 2 Characterization method of point cloud distribution.

## 4. Conclusions

TLS point cloud in the tunnel is mainly characterized by point cloud spacing and thickness. The point cloud spacing reflects the point cloud distribution density and point cloud trajectory. The point cloud thickness reflects the measurement accuracy of the measured surface. The point cloud generation mode consists of point cloud trajectory and measurement error. The point cloud trajectory is determined by the TLS scanning pattern and tunnel geometry. Therefore, the scanning pattern and measuring section length in the tunnel inspection scheme can be determined based on the point cloud trajectory generation principle using the point cloud spacing as an indicator. The measurement error is reduced from the laser incidence direction to reduce the undulation of the point cloud. This can improve the accuracy of tunnel 3D modeling and deformation measurement.

## References:

1) Ministry of Land, Infrastructure (2022): Guideline for Form Control Using 3D Measurement Technology.
2) Soudarissanane et al. (2011): Scanning geometry: Influencing factor on the quality of terrestrial laser scanning points.

 