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Research Paper

Evaluation of Geometric Error Sources for Terrestrial Laser Scanner

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Abstract

As 3D geospatial information is demanded, terrestrial laser scanners which can obtain 3D model of objects have been applied in various fields such as Building Information Modeling (BIM), structural analysis, and disaster management. To acquire precise data, performance evaluation of a terrestrial laser scanner must be conducted. While existing 3D surveying equipment like a total station has a standard method for performance evaluation, a terrestrial laser scanner evaluation technique for users is not established. This paper categorizes and analyzes error sources which generally occur in terrestrial laser scanning. In addition to the prior researches about categorizing error sources of terrestrial Laser scanning, this paper evaluates the error sources by the actual field tests for the smooth in-situ applications.The error factors in terrestrial laser scanning are categorized into interior error caused by mechanical errors in a terrestrial laser scanner and exterior errors affected by scanning geometry and target property. Each error sources were evaluated by simulation and actual experiments. The 3D coordinates of observed target can be distortedby the biases in distance and rotation measurement in scanning system. In particular, the exterior factors caused significant geometric errors in observed point cloud. The noise points can be generated by steep incidence angle, mixed-pixel and crosstalk. In using terrestrial laser scanner, elaborate scanning plan and proper post processing are required to obtain valid and accurate 3D spatial information.

Keywords : Terrestrial Laser Scanner, Point Cloud, Accuracy, Precision, Performance Evaluation, BIM

1. Introduction

Terrestrial laser scanner generates point cloud, based on the flight time of laser which is emitted from a scanner and reflected from targets. The terrestrial laser scanner can rapidly observe 3D shape of objects and has been applied in various fields such as Building Information Modeling (BIM), construction survey, and disaster management. For example, Cho et al.(2015) used terrestrial laser scanner in Antarctica and could achieve topographic map having accuracy of decimeter level. Hong et al.(2015) evaluated accuracy of terrestrial laser scanning in indoor BIM and verified the performance of terrestrial laser scanner. Moreover, for application of point cloud data in BIM, Lee et al.(2015) compared accuracy of terrestrial scanning with image-based 3D reconstruction technique and addressed that terrestrial laser scanner has better performance in obtaining detail information of building components.

In spite of the accuracy and precision of terrestrial laser scanner, the point cloud generated by scanner can havegeometric and radiometric errors caused by mechanical errorof a scanner, scanning geometry, and target properties. For effective application of theterrestrial laser scanner, performance evaluation is necessary to predict and quantify error sources which have significant effect on laser scanning data.

Geometric error sources in laser-based distance measurement and angular error of scanning mirror

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have been analyzed to developtheself-calibration method for the terrestrial laser scanner (Reshetyuk, 2006; Lichti, 2007; Schulz, 2007). In particular, Lichti (2010) defined the error sources with calibration parameters and analyzed the correlation among the parameters.

As well as the error sources in laser scanner system, scanning geometry and target properties also can have significant influence on the quality of observed point cloud (Lichti et al., 2005; Wunderlich et al., 2013). For example, Soudarissanane et al.(2011) conducted an experiment to assess the influence of scanning geometry on terrestrial laser scanning data.Furthermore, due to the characteristics of a laser signal, unpredictable noise points can be generated. For example, the noise points generated around edge components make observation quality of complex structure such as construction site into lower level. Before application of terrestrial laser scanner, the error factors must be evaluated and considered in design of laser scanning.

In this regard, this paper categorized and analyzed error sources which have been found in terrestrial laser scanning by experiments.The influence of mechanical errors in a terrestrial laser scanner was analyzed by simulation test with parameterized error sources andthe effect of scanning geometry and target property was evaluated from actual field test.

2. Error Sources in Terrestrial Laser Scanning

The terrestrial laser scanner generates point cloud data using the observed distance which is calculated from the flight time of laser signals. During the process, the mechanical property of scanner, scanning geometry and target property can cause observation errors. This paper categorized the errors into two types:interior error caused by mechanical error of terrestrial laser scanner device; and external errors affectedby scanning geometry and target property. The error sources can cause several problems in terrestrial laser scanning. The error sources can be summarized by Table 1.

Table 1. Error Categorization

Category	Error factors
Interior error	- Range error - Angular error
Exterior error	- Incidence angle - Mixed-pixel - Crosstalk

2.1 Mechanical Error

Terrestrial laser scanner emits thelasersignals in direction of horizontal angle (θ_h) and vertical angle (θ_v)which are pre-calculated by the device. The device calculates 3Dcoordinates (x, y, z) of target object combining the angles and the flight distance (ρ)which is derived from the laser flight time. The geometric equations can be represented by Eqs. (1), (2) and (3).

$$x = \rho \cos\theta_v \cos\theta_h \tag{1}$$

$$y = \rho \cos\theta_v \sin\theta_h \tag{2}$$

$$z = \rho \sin\theta_v \tag{3}$$

According to the above equations, the mechanical error is caused by the errors in the flight distance of laser, horizontal angle and vertical angle(Reshetyuk, 2006; Lichti, 2007; Schulz, 2007; Park et al., 2013).The laser flight distance can be calculated from the laser signal flight time. In measuring distance by laser,laser flight time errormight occur by bias derived from the internal signal delay of laser flight time measurement instrument. In addition, the emittance direction of laser signal is determined by the function of rotating mirror.The mechanical errors of horizontal and vertical rotationof mirror cause angular errors.

2.1.1 Range Error

The range distance between scanner and target can be determined by flight time of laser signal and Eq. (4) represents basic formula that calculates the distance between scanner and the object.

$$\rho = \frac{c}{n}\frac{\tau}{2} \tag{4}$$

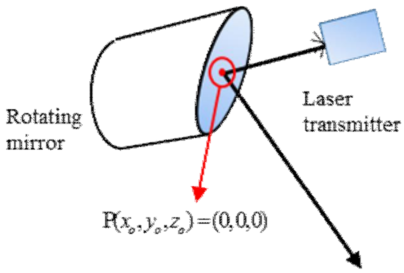

Figure 1. Disagreement between laser zero point and center of rotating mirror.

where, ρ represents distance to object, c for speed of light, n for refraction coefficient and t for time difference. The key of accuracy in laser scanning is to figure out the time difference precisely as possible. When the calculation is not accurate, not only the distance can be distorted, but also the angular location can be wrong. Fig. 1 describes the disagreement between laser zero point and center of rotating mirror.

As shown in Fig. 1, the scanning center should be located on the center of the rotating mirror. However, when the distance between rotating mirror and laser transmitter is miscalculated, it causes the laser point fall into the wrong position and error in the calculation of the object location.The error factor is called range error.

2.1.2 Angular Error

Fig. 2 describes top view of internal system of terrestrial laser scanner.

When the rotating mirror is correctly assembled, the laser beam would fly exactly vertical to the horizontal axis as depicted by dashed line in Fig. 2. But when the rotating mirror is dislocated, the error would occur as depicted by solid linein Fig. 2. This kind of erroris called collimation error.

Fig. 3 describes side view of internal system of terrestrial laser scanner.

Same as the case of collimation error, when the rotating mirror is assembled correctly, the beam would go parallel to the vertical axis as depicted by dashed line in Fig. 3. But when the dislocation occurs, the laser beam route would also make an error as depicted by solid line in Fig. 3. The error factor is called vertical angular error.

As the mirror rotates for observation, laser would make a circle as shown in Fig. 4.

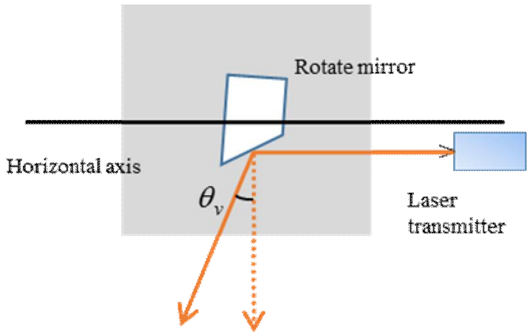

Figure 2. Top view of rotatingmirror

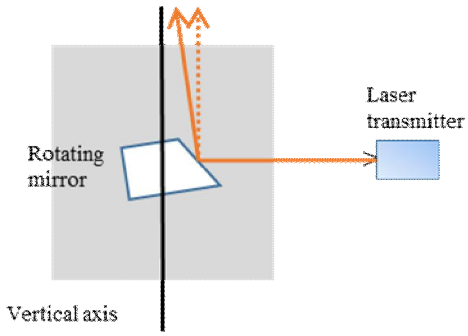

Figure 3. Side view of rotating mirror.

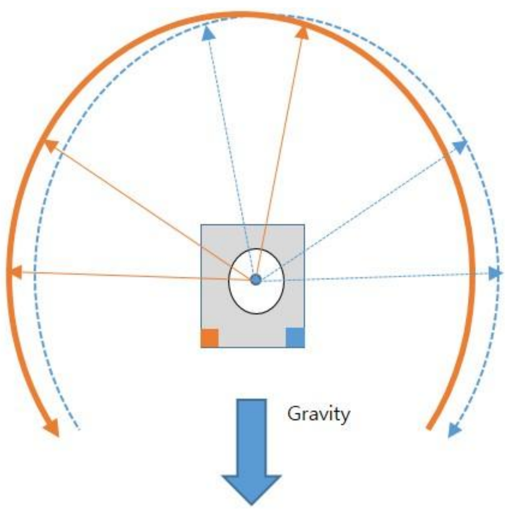

Figure 4. Front view of rotatingmirror.

Due to the gravity and mechanic error, the rotation would be slightly instable. So the circle that generated by the laser would be also slightly crushed. This can be detected when the user locates the scanner opposite in 180 degree to the original pose as depicted in dashed line. This discordance is called vertical axis error.

2.2 Scanning geometry and target property

Since terrestrial laser scanning generates point clouds with laser flight time and reflection intensity, laser incidence angle to the target object and target properties as shape and material quality might influence to the point cloud quality in addition to the mechanical error sources.

2.2.1 Laser incidence angle

Because the flight time is measured by the signal reflected from a target, the laser incidence angle directly influences to the point cloud quality.When the incidence angle condition is not properly fulfilled, the point cloud may not be generated even using long-range scanner within effective distance (Soudarissanane et al., 2011). These characteristics may cause crucial defect in observing road, tunnel, building and slope.

2.2.2 Mixed-pixel

At the edge of target objects, which makes a discontinuous plane in generating point cloud, ghost pointsmight occur. The ghost points generated at the edge is generally called mixed-pixel(Hebert and Krotkov, 1992; Tang et al., 2009). The mixed-pixel is caused when the laser signal is partly reflected at the edge of a target object. The mixed pixel should be significantly considered in observing facilities with complicated structure asplants and bridges.

2.2.3 Crosstalk

When a laser signal is reflected from an object, the material and color can has an influence on measuring laser flight time of the target as well as received signal intensity (Amann et al., 2001; Pesci and Teza, 2008). The phenomenon generates noisesin point cloud and is called crosstalk (Hebert and Krotkov, 1992). The noise occurrence might affect to the precision of point cloud. In particular,phenomenon is often found in observing Black & White (BW) targets for registration and degrades the precision of point cloud.

3. Experiments

3.1 error

Terrestrial laser scanner is expensive and precise equipment so the mechanical errors aregenerally too smallto analyze (Lichti, 2010; Park, 2013). To evaluate influence of the mechanical errors in a terrestrial laser scanner, we conducted simulation analysis.

To identify the interior error sources, the mechanical error factor must be included in the geometric equation (Eqs. (1), (2) and (3)). For the simulation, the model proposed by Lichti(2010) and Reshetyuk (2010) was adopted. The error model can be represented by following Eqs. (5), (6) and (7).

$$\rho = \sqrt{x^2 + y^2 + z^2} = \rho_0 + k_d + e \tag{5}$$

$$\theta_h = \arctan(\frac{}{x}) = \theta_{h0} + k_{h1}\sec\theta_v + k_{h2}\tan\theta_v + e \tag{6}$$

$$\theta_v = \arctan\frac{}{\sqrt{x^2 + y^2}} = \theta_{v0} + k_v + e \tag{7}$$

where, ρ_0, θ_{h0}, and θ_{v0} represent true value of distance, horizontal angle and vertical angle respectively. And also k_d, k_{h1}, k_{h2} and k_v represent range error, collimation error, vertical angular error, and vertical axis error, respectively.

3.2 Evaluation of influence of scanning geometry and target property

Theexperiment was conducted at the underground parking lot of Engineering Park in Yonsei University. Fig. 5 shows the experiment site and terrestrial laser scanner.

A set of targets shown in Fig. 7 was established at the distance of 55m. And scanning condition for point resolution was set as 6.136mm/10m.

Figure 5. Experiment site and terrestrial laser scanner

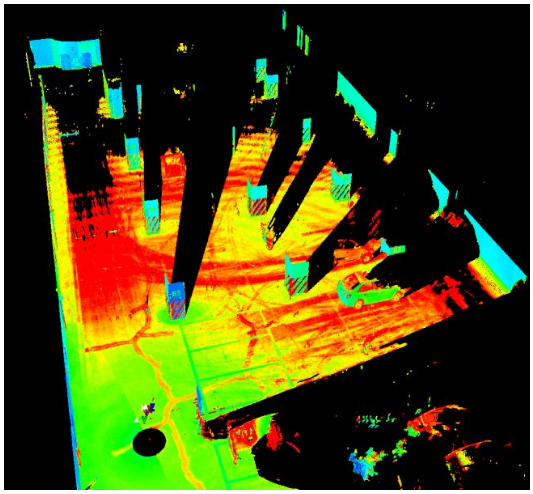

Figure 6. Point cloud data acquired by Focus3D

Table 2. Specification of terrestrial laser scanner

Terrestrial laser scanner	Focus 3D
Manufacturer	Faro
Instrument type	Amplitude Modulated Continuous Wave (AMCW)
Field of view (vertical / horizontal)	Hori : 360° Vert : 305°
Maximum measurement range	120m
Maximum scan rate	976,000 points/sec
Maximum Resolution	0.6mm @ 10m 0.95mm @ 25m

Focus 3D from FARO corporation was used for the experiment. Table 2 summarizes the specification of Focus 3D.

The Focus 3D uses the signal of Amplitude Modulated Continuous Wave (AMCW) which measures flight time of laser signal based on phase difference. The maximum effective range is about 120m.And point density of scanning in the experiments was set by 0.6 mm at 10 m. Fig. 6 shows the point cloud acquired by Focus 3D.

To analyze the error sources, O-shape target were designed. To successfully identify the target in point cloud, point density and size of target were considered.Fig. 7 represents the design of set of targets.

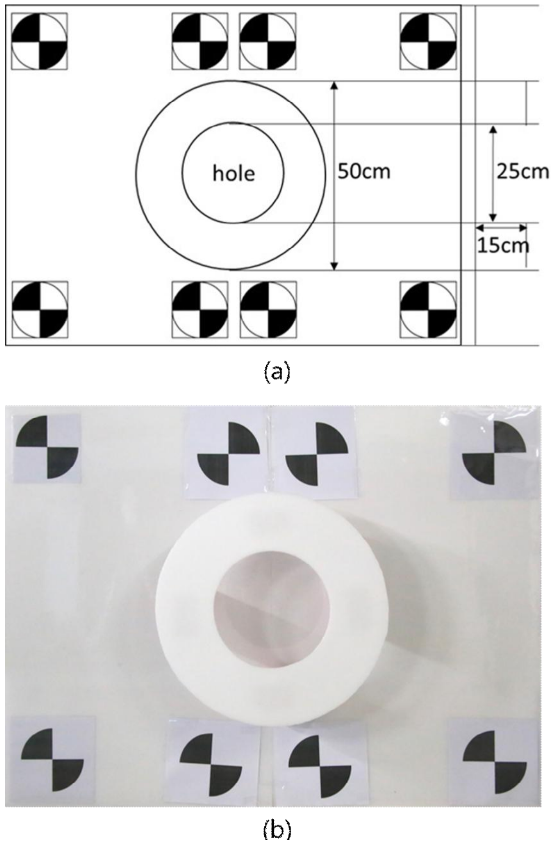

Figure 7. Set of targets for error factor analysis: O-type target: (a) specific design, (b) picture of real target.

4. Experimental Results

4.1 Influence of mechanical error

With respect to gradual changes of $\kappa_d, \kappa_{h1}, \kappa_{h2}, \kappa_v$, point coordinates of target objects would change. To analyze change (dx, dy, dz) of point coordinates, a simulation test was done. The test applied simulated biases of range and angular error values on twofixed target point coordinatesobserved in low vertical angle ($(x, y, z) = (5, 50, 2)$, 3.7623 degree) and high vertical angle($(x, y, z) = (5, 5, 11)$, 62.0725degree), respectively. And the simulation followed error equations presented on prior chapters(Eq. Eqs. (1), (2) and (3), Eqs. (5), (6) and (7)). The results from $(x, y, z) = (5, 50, 2)$ is represented in solid line and the result from $(x, y, z) = (5, 5, 11)$ are represented in dashed line in following Figs. 8, 9, 10 and 11, respectively.

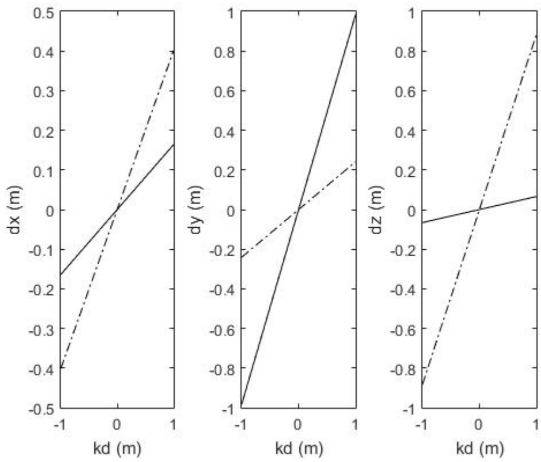

Figure 8. Correlation between κ_d and point location

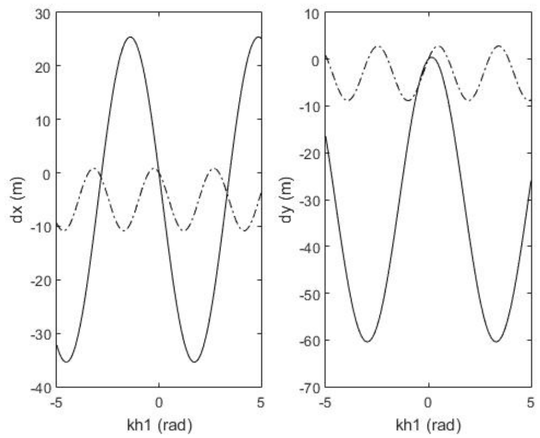

Figure 9. Correlation between κ_{h1} and point location

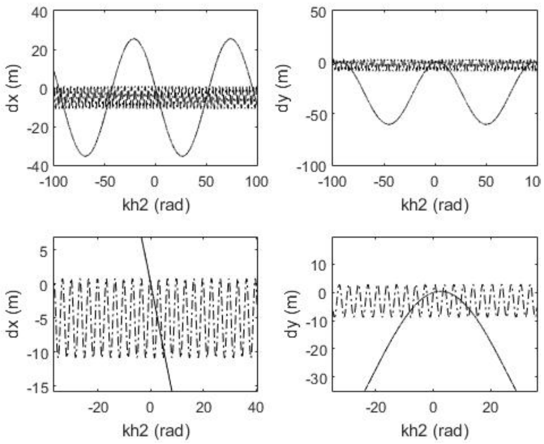

Figure 10. Correlation between κ_{h2} and point location

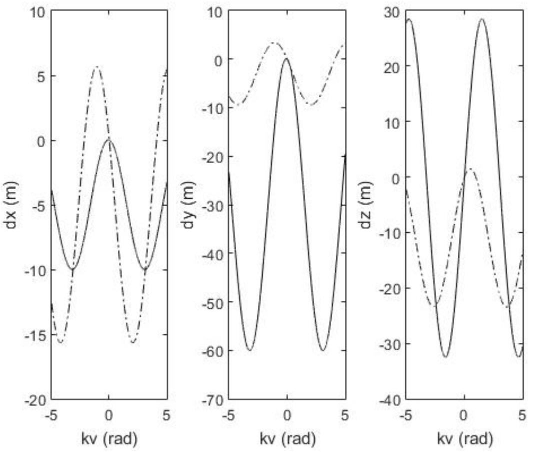

Figure 11. Correlation between κ_v and point location

In Fig. 8, correlations between κ_d and point location errorsshowed linear relation since Eq. (5) is in linear form. The error amount of target location estimation seems to differ according to the target location.

As shown in Figs. 9, 10 and 11, correlationsbetween $\kappa_{h1}, \kappa_{h2}, \kappa_v$ and point location error wererepresented in sine functional graph since the variables are related with trigonometrical functions.Especially on Fig. 10, additional graphs were shown whose range of x axis was shorten for readability. Since frequencies of graphs were highly different. Alike the case of K_d correlation, the graphs representing change amounts of target location estimation including frequency, width and wavelength differed in shape according to the target location.In particular, K_{h1} and K_{h2} parameters had no affection to the point location error in z direction.

4.2 Incidence angle

According to the incidence angle of laser signals, point density is affected and noise point might be generated. Fig. 12 shows the point density and ratio of noise points according to the incidence angle. A data set of Point cloud from the bottom of parking lot was extracted in linear direction as depicted in Fig. 12 (a).

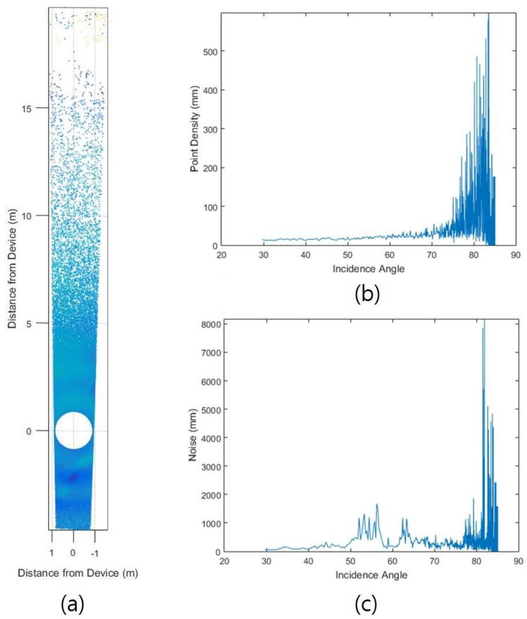

Figure 12. Error occurrence according to the laser incidence angle: (a) extracted point cloud datain linear direction to analyze the occurrence of error according to the laser incidence angle, (b) point density changing with respect to the laser incidence angle, represented by the distance between the nearest points, (c) noise ratio with respect to the laser incidence angle.

As shown in Fig. 12, the point cloud quality was stable until the incidence angle reaches certain incidence angle. According to the experiment and analysis, the point density represented by the distance from the scanner becamerapidly sparse over the incidence angle of 70o. And noise ratio rapidly increased when the incidence angle exceeds 75o.

4.3 Mixed pixel

Mixed pixel is wrong point data collected at the edge of the object. Fig. 13 shows the point cloud observing the O-shaped target and mixed-pixels can be analyzed from the point cloud.

As shown in Fig. 13, the mixed pixel could be identified at the edge of the O-shape target. To analyze the number of the noise points, plane components were extracted. The brief process and results are summarized in Fig. 14.

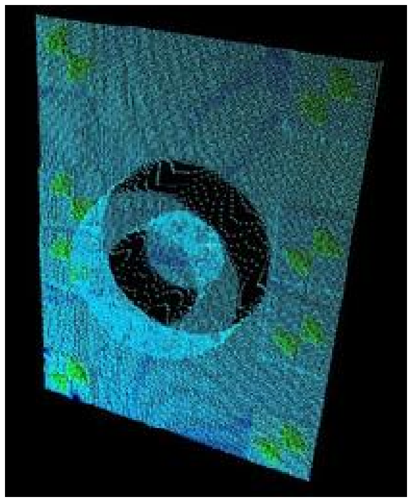

Figure 13. Mixed pixel which occurred around the edge of the target.

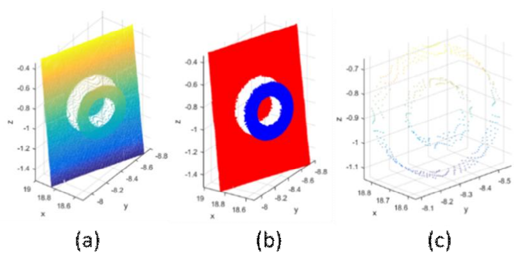

Figure 14. (a) Raw data, (b) plane extraction, (c) mixed pixel

Table 3. Result of evaluation for Mixed Pixel occurrence

Terrestrial laser scanner	Focus 3D
Target type	O-type
Point density	4mm @ 10 m
Distance	40m
Number of mixed pixel	487

As shown in Fig. 14 and Table 3, hundreds of mixed pixels were remained after extracting the plane components from the original point cloud. The mixed pixel can be critical problem in laser scanning in pipe lines and columns in plant facilities and buildings.

4.4 Crosstalk

Crosstalk is a factor that relies on the color and qualityof the object material. In particular, the phenomena makes it difficult to use targets for registration of multiple point cloud sets. Fig. 15shows point cloud observing a BW target which is generally used for registration.

As shown in the Fig. 15, the point clouds at the black side were splashed from the target plane. The number and rate of noise points are shown in Table 4.

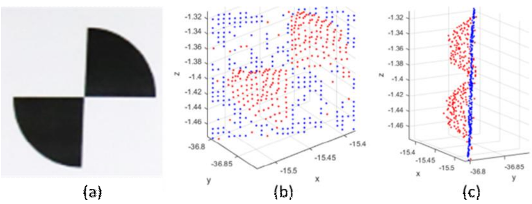

Figure 15. (a) BW target used to analyze Crosstalk; (b) Point cloud represented with respect to front view (red: black part, blue: white part); (c) Point cloud represented with respect to intensity side view.

Table 4. Result of evaluation for Crosstalk occurrence

Terrestrial laser scanner	Focus 3D
Distance	40m
Number of points	756
Number of noise points	241 (32%)
Mean Error	14 cm
RMSE	16cm

5. Conclusions

Terrestrial Laser Scanner has superb ability in generating 3D spatial information. However, the data quality might be affected by internal and external factors. Frequently, the error factors cause critical problems in application of terrestrial laser scanning data. In this paper, the error factors were categorized and its influenceswere evaluated by experiments.

First, Mechanical errors are caused by the internal condition of the device. Mechanical errors consist of range error and angular error. Range error is caused by the miscalculation of laser flight time between laser beam transmitter and rotating mirror. And angular error is caused by dislocation of rotating mirror. By the simulation test, the way that each mechanical error parameters have influence on the point location was identified. Parameter k_d had linear relationship with the point location error. And the other parameters, k_{h1} k_{h2} and k_v had sine functional relation with the point location errors.

Second, errors can be caused by the scanning geometry and target property. The errors were identified with experiments using specific sets of targets. With increasing laser incidence angle, error rate of point cloud rapidly increased when the angle exceeded certain degree, approximately 70o. And mixed pixels were identified to occur on the edge of the target object. Target color also had influence on the quality of point cloud. On the black side of BW target, point clouds were splashed from the target plane and the error is called crosstalk.

In conclusion, in using terrestrial laser scanner, elaborate scanning plan and proper post processing are required to obtain valid and accurate 3D spatial information.

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