Evaluation of Factors, Influencing the Accuracy of the Digital Model, Obtained by Laser Scanning

Gergana Antova 1

1 University of Architecture, Civil Engineering and Geodesy, 1 Hristo Smirnenski Blvd., Sofia 1164, Bulgaria

antova_fgs@uacg.bg

Abstract. Measurements in terrestrial laser scanning (TLS) are not perfect and are subject to errors caused by various factors affecting the quality of the capture process and the resulting final product. Careful consideration of all these factors and errors provides a good basis for assessing the quality of the data and the information received. The accuracy of the 3D model obtained from laser scanning is influenced by the density of the measurements and the modelling methods. 3D modelling algorithms allow accuracy to be improved, but modelling software cannot solve all the problems, and it is impossible to achieve high quality 3D modelling without taking into account the factors that affect the accuracy of the measurements. The investigation of error sources in TLS measurements is rather complicated due to the large number of influencing factors that are interconnected. In addition to angular and longitudinal measurements, most scanning systems also offer a measure of the intensity of the reflected signal. Because the TLS is a non-reflective geodetic technology, it means that the measurement results are highly dependent on the reflectivity of the materials. The energy of the reflected signal depends on the following physical factors: object material properties, surface colour of the object, surface temperature, surface humidity, illumination. From the experimental studies it has been confirmed that the illumination and humidity of the scanned surfaces have a significant impact on their reflecting ability and the density of the received point cloud. Evaluation of digital model accuracy is made with a plane approximation and comparison with control points. Areas with different point densities were created in order to analyse the accuracy of 3D model and to determine the optimum scanning density.

1. Introduction

The Terrestrial Laser Scanning (TLS) technology is increasingly used in geodetic practice, because of the 3D surface measurements with good quality in very short time. After the measurement, the point cloud is further processed and modelled for use in other applications such as deformation applications [1], building information modelling [2], 3D cadastre [3], cultural heritage documentation etc. Since the error in the individual point affects the end product, there is a need for a good description of the quality of the points. Manufacturers provide basic technical specifications that are often obtained in laboratory conditions. In practice, the quality of the individual point is influenced by four major factors. Three of them are described in chapter 2, namely, instrumental errors, atmospheric influences and properties of the object's material. All these factors influence the accuracy of a single point by adding noise or changing the intensity and the shape of the broadcast signal. In chapter 3 it is shown how the accuracy of the measured distance depends on the quality of the received signal. The influence of the factors influencing the accuracy of ground laser scanning of concrete dam walls is summarized. The dependence
of the illumination and moisture of the scanned surface on the density of point cloud and accuracy of the digital model [4] of the object is determined. The accuracy of the individual measurement with terrestrial laser technology and the digital model obtained from a point cloud by an approximated surface, as well as an evaluation of the model by difference of control points, is presented.

2. Sources of errors in terrestrial laser scanning

The quality of the individual point in a point cloud from TLS measurements depends on 4 main factors:

- Tool errors and hardware limitations;
- Atmospheric influences;
- Object (surface properties);
- Scan geometry (reflection angle and distance to the object).

2.1. Errors related to the shape and character of the scanned object

The first and major source of these errors is the reflectivity of the surface of the object. Because the TLS is a non-reflective geodetic technique, it means that the measurement results strongly depend on the reflectivity of the materials, which also greatly affects the Signal-to-Noise-reduction (SNR). The energy of the reflected signal depends on physical and geometric factors. The physical factors include material properties of the object, surface color, surface temperature, moisture of the object, illumination. Geometric factors include reflection angle and roughness of the surface, which determines how the energy dissipates [5, 6].

2.2. Errors related to the external conditions

2.2.1. Errors due to the spread of rays in the atmosphere. The effects of beam propagation are distortion of the shape of the impulse return and damping. This leads to a reduction of the intensity of laser light as a result of scattering and absorption (water vapor, carbon dioxide, ozone).

2.2.2. Influence of unfavorable external conditions on measurements with terrestrial laser scanners. In case of measurements with terrestrial laser scanners, it is meant: fog, haze and rain. Snow is not mentioned, because most laser scanners do not work at temperatures below 0 degrees Celsius.

2.2.3. Methodological errors. This set includes setup errors (scanning density, scan mode) as well as the errors associated with the point cloud registration [7].

2.2.4. Influence of external radiation. The emission of light from an external source (lamps, sunlight, etc.) can affect the accuracy of the measured range if it is significantly stronger than the captured laser energy.

2.2.5. Errors due to instability and vibration of the scanner during measurements. The wind may cause intermittent translational and rotational fluctuations of the laser scanner during the measurements.
2.3. Analysis of factors influencing the accuracy of TLS
The accuracy of measurements depends on the measurement deviation from the true value. The true value can be obtained from another more accurate measurement method.

The precision of measurements is defined by the number of measurements (how many times the magnitude has been measured). If one distance is measured several times and the arithmetic mean is calculated, the precision is a measure of how close to the average is each measurement (mean square error). It defines measurement deviations when using the same tool several times for the same purpose over a small amount of time. Small variations of these repeat measurements define good measurement stability. The definition of measurement precision does not require a true value but is determined only on the basis of the measurements. Reliable measurement is the accurate measurement. Precision and accuracy depend on random and systematic errors.

Manufacturers of laser scanners use the term "noise" considering precision. When measuring distances with a spinner, the precision of the points depends on the distance and the properties of the surface. Longer distance results in less precision. The black surface absorbs energy, which reduces the range of the measured distance and the resulting signal, resulting in a low precision. The opposite is also true - a white surface reflects the signal and provides greater precision over a long distance. It should be noted that accuracy is more important than precision, because a precision instrument may be inaccurate due to a systematic error.

The accuracy of the non-reflective measurement of distance is influenced by the factors described in previous section. All of these parameters, influence the strength of the signal and hence the accuracy of the measured distance. Therefore, no division of factors can be made. For example: a bright surface with a large reflection angle and a large distance from the scanner is equal with a dark surface with a small angle of reflection and close distance. All these factors, however, affect the measured intensity values. In addition, the stochastic properties of the range finder can be obtained by the intensity values [9]. At this point, it is shown how the accuracy of the individual point in a cloud can be assessed.

TLS measures the reflected signal from the object and the result is a point cloud. Assuming that each surface can be considered a plane in a local area, the object can be represented as many small planar pieces. The resulting plane parameters and residuals can be used to determine the quality and noise level of the individual points in a cloud.

The equation of a plane can be represented as:

\[ f(x, y, z) = PN + d = 0 \]  
(1)

where \( P = [x, y, z] \) are the coordinates of a plane point, \( N = [a, b, c] \) is the normal vector of the plane and \( d \) is the distance from the plane to the beginning of the coordinate system:

\[ f(x, y, z) = ax + by + dz + d = 0 \]  
(2)

The most commonly used method is the Least Square Adjustment (LSA), minimizing the residuals in one direction, e.g. \( Z \):

\[ z_i = \frac{(ax_i + by_i + d)}{c} \]  
(3)

To compare the quality of an area to another, the standard deviation \( \sigma \) used that counts the number of points in the area. It is an indicator of the precision of the residuals calculated on the approximated plane:
\[
\sigma = \sqrt{\frac{\nu^2 \nu}{n-k}},
\]

where \( n \) is the number of points (measurements) and \( k \) is the number of unknown parameters \((k = 3)\). Increasing the number of points increases the precision of the specified plane parameters. Independence from the coordinate system can be achieved by minimizing the perpendicular distance to the model.

3. Evaluation of the accuracy of a digital model from point cloud

The experiment is performed using two point clouds derived with two different instruments in different circumstances – laser scanner and scanning station situated in 100 m and 350 m distance from two dams.

Cankov Kamak dam is situated in Rodopi Mountain in the southern part of Bulgaria. The structure, built in the 2014 is a concrete double arch dam with 130 m maximum high and 468 m length on the crest. Laser scan measurements from one fix scan position is made in order to minimize the registration error. The instrument LeicaNovaTM50 data acquisition with precision (also known as scanner noise) of the measurement at 350 m was measured at 1.5 mm on this instrument (given as one standard deviation), while accuracy was of the order of 2 mm up to 500 m. 500 thousand points are measured with density of 20 cm.

Studena dam is situated in west part of Bulgaria 40 km west from the capital city Sofia. The dam is a concrete buttress with 55 m maximum high and 259 m in length in the crest. The measurements were performed with scanner Leica Scan Station C10 with a range up to 300 m and accuracy 6 mm and speed of scanning 50000 points per second. The instrument was situated 100 m from the dam. 15 million points are measured with density of 2 cm.

3.1. Single point accuracy

The single point accuracy of a point cloud has been calculated by approximating the plane, as described in point 2.3. The obtained accuracy for the Tsankov Kamak dam wall is \( \sigma = 13 - 15 \) mm depending on different scan geometry (distance and reflection angle). Better approximation and a smaller mean square error are obtained by using a 2nd degree polynomial for Tsankov kamak, which is logical in the case of a double arc shape of the wall.

For Studena dam, the same cloud precision study was done by approximating a plane of a 3-square-meter part of the surface. The resulting mean square error for the single point accuracy is \( \sigma = 5 \) mm. The difficulty in this case is to find a smooth surface, given the big tonality disruption.

3.2. Comparison with control points

The investigation is made in two methods: 1) Differences with directly measured points with total station and 2) Differences with points excluded from the cloud.

3.2.1. The accuracy of the digital model by differences with direct measurements to 150 points from the wall measured at Tsankov kamak dam in September is evaluated. A triangular irregular network (TIN) was created from the cloud of points and the heights of the directly measured points were extracted. Statistical analysis of the differences confirming the assumption of normal distribution was made. The standard deviation \( \sigma_y = 15 \) mm was calculated.

3.2.2. The accuracy of the digital model of the Tsankov Kamak dam is calculated by differences with points previously excluded from the cloud. A VisualBasic program was written for to exclude 1 per 1,000 points that are recorded in a separate file.
Figure 2. Interface of the point cloud sampling program

The comparison was performed in the CloudCompare software. Excluded cloud points are compared to TIN surface created by the reduced cloud applying Cloud-to-Mesh (C2M) algorithm. The results are visualized with a color scale in Figure 3 as well as a distribution histogram. Average value of 3 mm is calculated. A statistical analysis of the differences, which confirm the thesis for a normal distribution with a mathematical expectation of 0.79 mm and standard deviation $\sigma = 15$ mm, was made.

Figure 3. Preview the differences between the surface and the points excluded from the cloud

In order to see the influence of point density on the digital model accuracy, the point cloud is reduced to a density of 0.5 m and 0.8 m. The same procedure is applied and the same result is obtained.

3.3. Analysis of the impact of point cloud density on point cloud accuracy
The analysis is made by approximating a 2-degree surface area of the dam wall scanned at 5 cm. A part of the cloud with a 5 cm density including 44763 points is cut. A second-degree surface over the point cloud is approximated. The estimation is made for a density of 5, 10, 20, and so on, over 10 cm to 100. The standard deviation of the approximated surface (Table 1) begins to grow at a point density of more than 80 cm.
Table 1. Standard deviation of the approximated surface at different cloud point density

| Point cloud density | Number of points | Standard deviation, mm |
|---------------------|------------------|------------------------|
| 5 cm                | 44763            | 14.6                   |
| 10 cm               | 13596            | 14.7                   |
| 15 cm               | 5529             | 14.7                   |
| 20 cm               | 3420             | 14.7                   |
| 30 cm               | 1050             | 14.7                   |
| 40 cm               | 898              | 14.9                   |
| 50 cm               | 590              | 14.7                   |
| 60 cm               | 421              | 14.4                   |
| 70 cm               | 318              | 15.1                   |
| 80 cm               | 252              | 15.1                   |

Figure 4. Part of a point cloud

3.4. Analysis of the intensity of the reflected signal as a result of sunlight

The impact of illumination on the intensity of the reflected signal was evaluated: 283146 points were measured in sunny day and 459316 points in cloudy day. There is a reduction in the intensity of the reflected signal of the illuminated areas (Figure 5), and hence the decrease of the density of the measured point cloud. The left half of the dam is always in the shadow and the intensity of received signal is low, the right part of the dam (in red) is illuminated by the sun and the intensity of received signal is high.

Figure 5. Map and histogram of the intensity of the measured points in sunny weather (left) and cloudy weather (right)

Evaluation of the influence of illumination on cloud density for the sunny area - 69148 points in sunny weather and 165488 points in cloudy weather (Figure 6). A reduction factor \( K = 2.39 \) was calculated. There is a noticeable reduction in the density of points in the sunny areas.
3.5. Analysis of the moisture of the material

To measure the effect of the surface moisture on the point cloud intensity, a comparison of the two point clouds obtained by measuring the surface of the dam in different conditions. There is a considerable loss in the density of the cloudy part when the surface moisture is high.

**Figure 6.** Cloud density for the sunny area

Evaluation of the influence of the illumination on the cloud density of the shadow wall part (Figure 7): 213998 points in sunny day and 293968 points in cloudy day: reduction $K = 1.137$.

**Figure 7.** Cloud density for shadow part
of intensity at high moisture of the wall (high water level in the lake), especially the overflow (points in blue on Figure 8).

**Figure 8.** Map of intensity of the reflected signal at high moisture of the material

**Figure 9.** Map of intensity of the reflected signal at low moisture of the material

4. **Conclusions**

In practice, the end user has limited influence on the factors influencing the accuracy of laser scanning distance measurements. It is difficult to change parameters such as rotation of the mirror or object material in order to obtain better measurement conditions. But the atmospheric conditions and the scanning geometry, as the position of the scanner to the object, are selected by the user. Choosing a lower scanning density reduces scanning time, optimizes costs, and facilitates processing, but must be consistent with the requirement not to lose surface representativeness. In cases where TLS measurements will be used to detect small bursts and deformations on the surface of the dam, the full cloud point potential should be handled.

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