Variability of roughness parameters calculated using data obtained by TLS depending on scan resolution and beam's angle of incidence

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Spatial data obtained by Terrestrial Laser Scanning (TLS) can be used in order to create various inventories and analyses of the surveyed surfaces. This paper presents a use of orthogonal regression line in order to identify the beam's incidence angle on the surveyed surface as well as identification of roughness parameters using data obtained by terrestrial laser scanning. Accuracy of the visualisation of the surface and roughness parameters, in particular Ra (mean arithmetic deviation of surface roughness profile forming the average line) are closely correlated to the scan resolution of the evaluated area. Presented analyses indicate a need to identify areas with uniform visualisation [1,2] in the compared scans.
Keywords: Terrestrial Laser Scanning (TLS), roughness, orthogonal regression

Introduction

At present, terrestrial laser scanning (TLS) is one of the most modern and rapidly developing geodetic measurement techniques. It allows for an extremely quick collection of measurement data forming, so-called point cloud. Not only is a point cloud a complete set of information on an object's shape and dimensions [3] but also, owing to the recorded laser beam reflection strength (Intensity), about its texture and structural diversity. Spatial data obtained by the TLS method is most often used as a basis for classic inventories. Terrestrial laser scanning is also used in order to monitor and identify shifts and deformations in various engineering objects [4,5,6].

Table 1. Chromatographic, spectrophotometric, and mass spectrometric data of the analyzed products of neobetanin oxidation

Lifetime category	Assumed lifetime [year]	Exemplary objects
1	10	Temporary constructions
2	10-25	Replaceable construction elements, ex. crane girders, bearings
3	15-30	Agricultural facilities and related structures
4	50	Buildings and other public construction objects
5	100	Monumental constructions, bridges and other engineering constructions

Condition evaluation of concrete surfaces

European standard EN 1990 [7] contains recommendations concerning assumed object lifetime of various structures (table 1).

Hydrotechnical structures fall into 5th class category with assumed lifetime of 100 years. Nevertheless, assumed lifetime should not be understood as the service life of the object, but as a period when no major repairs should be required. Despite those legal regulations, due to varied quality of concrete used to build concrete dams, systematic periodic evaluation of the object's condition is necessary.

Hydrotechnical concrete forms a group of concrete types that are waterproof and wear resistant. Hydrotechnical concrete is expected to be waterproof, frost resistant, wear resistant and characterised by low heat of hydration and low shrinkage. This entails reduction of cement quantity allowing for reduction of dissipated hydration heat. Reduction of cement quantity causes an increase in concrete surface roughness. Changes of concrete surface roughness parameters during exploitation may indicate surface erosion, increase in dampness and an increase in plant overgrowth.

Surface dampness is an important characteristic in the evaluation of surface condition. Changes of this parameter, as well as of roughness parameters, may point to an increase in filtration therefore have an impact on an object's operational safety.

As regards large massive concrete objects like water dams, a laser scanning technique can be used as a source of information on an object's condition. An inventory can be used for:

– creation of a complete inventory of the object and its surroundings

- evaluation of the object's condition, particularly evaluation of concrete surfaces located in places rendering visual monitoring inapplicable [1],
- creation of new numerical models and verification of previously existing models concerning the object [8],
- verification and completion of behaviour models [9],
- determining possible shifts and deformations (periodical control measurements).

Research

Work carried out by the team from Chair of Engineering Geodesy, Measurement and Control Systems, Warsaw University of Technology, focuses on formulation of methodology concerning precise determination of shifts and deformations (expected accuracy of change below 0,5 cm) as well as creation of algorithms evaluating surface condition using distribution and changes in recorded Intensity values [10]. Geometrical and statistical analysis of point clouds that takes roughness into consideration can serve as a different method of evaluating the surface's condition.

Essential conditions required in order to maintain high reliability of the carried out analyses [2]:
- uniform measurement precision on the whole analysed surface,
- uniform (or close to uniform) distribution of the recorded points on the analysed surface.

Angle of incidence

Angle of incidence is a very important element in point cloud analysis. It has an enormous impact on quality of obtained TLS data. When evaluating surface condition, its angle of incline may determine surface susceptibility to external factors like rainfall, plant overgrowth or internal stresses resulting from internal work of the structure that may cause erosion processes. In order to identify areas with uniform visualisation as well as to carry out preliminary evaluation of surface condition it is essential to determine the laser beam's angle of incidence on the evaluated surface, that is the angle between the beam falling on the surveyed surface and the normal to this surface in the point of incidence (0÷90°) (fig. 1). This task can be easily resolved with the use of orthogonal regression, which was described in [2]. In order to determine the angle of incidence in any given point (Xi, Yi, Zi) the equation for the line passing through said point and the centre of the instrument's optical system that is the centre local coordinate system of the point cloud, has to be determined. The presented calculation procedures are realised on a horizontal XY projection plane. This allows for the application of simple and intuitive orthogonal regression formulas. In many tasks it is not necessary to carry out complicated calculations in order to identify the best-fit surface. Analyses performed by the authors of this paper indicate that the results of function parameter calculations approximating the plane into selected fragments of point cloud, carried out in data processing software packages like Leica Cyclone or Z+F LaserControl (automatic built-in functions), are not determined and provided with sufficient accuracy. This results in an inability to carry out calculations and introduce various corrections, for example, the influence of a beam's angle of incidence. These types of built-in functions are mainly used for data presentation.

By approximating the plane with orthogonal regression line (1) and knowing the equation for the line passing through the centre of the measurement system (2) and the selected point, it is possible to determine the point of intersection (3) of those lines, which is a complement of the beam's angle of incidence (δ) (4).

Equation for regression line:

$$x_r \cos\beta + y_r \sin\beta - p_r = 0 \quad (1)$$

Equation for the line passing through the centre of the coordinate system and the point for which the angle of incidence is being determined:

$$x_p \cos\alpha + y_p \sin\alpha - p_p = 0 \quad (2)$$

Point of intersection of the above mentioned lines (1) and (2):

$$\tan\gamma = \left| \frac{\frac{-\cos\beta}{\sin\beta} - \frac{-\cos\alpha}{\sin\alpha}}{1 + \frac{-\cos\beta}{\sin\beta} * \frac{-\cos\alpha}{\sin\alpha}} \right| \quad (3)$$

Beam's angle of incidence:

$$\delta = 90^\circ - \gamma \quad (4)$$

In order to verify correctness of this approach, the theoretical value of the angle of incidence was compared to the one obtained using orthogonal regression line. This comparison reveals that for a randomly selected concrete surface (A) distribution of absolute values of angle difference (theoretical – specified during the experiment by appropriate placement of the sample and the one identified through orthogonal regression) depends on the selected

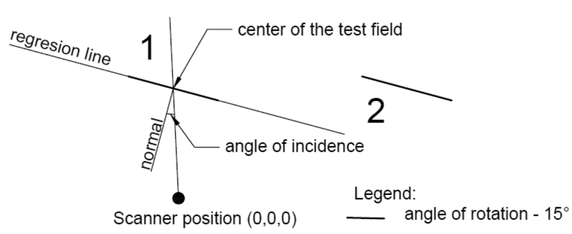

Figure 1. Definition of angle of incidence [2]

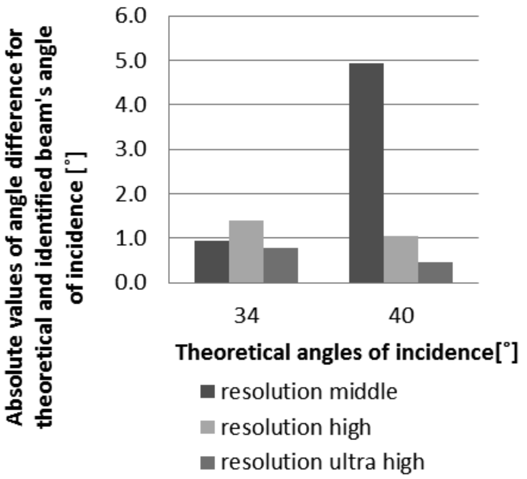

Figure 2. Graph presenting absolute values of angle difference for theoretical and identified beam's angle of incidence for surface A and theoretical angles of incidence equal to 34° and 40°

Table 2. Summary of angle of incidence values

Placement of the sample	Scan resolution setting	Surface A	
		Theoretical angle of incidence [°]	Identified angle of incidence [°]
1	m	34,0	33,1
	h	34,0	32,6
	u	34,0	33,2
2	m	40,0	35,1
	h	40,0	38,9
	u	40,0	39,5
3	m	44,0	49,0
	h	44,0	43,5
	u	44,0	44,2
4	m	60,0	61,9
	h	60,0	60,4
	u	60,0	59,4

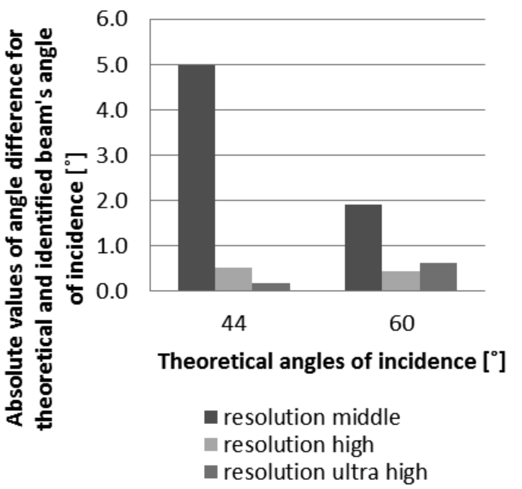

Figure 3. Graph presenting absolute values of angle difference for theoretical and identified beam's angle of incidence for surface A and theoretical angles of incidence equal to 44° and 60°

scan resolution (table 2). For the lowest resolution setting - "middle", the differences are up to 5°; for "high" and "ultra high" settings, the differences oscillate around 1°(table 2, fig.2, fig.3).

Surface roughness

Roughness is an attribute of a surface that can be defined as a collection of small surface unevennesses that can be identified optically or detected mechanically which do not result from the said surface's shape and their size depending on the material type and undergone processing. Therefore roughness is an optically noticable or mechanically detectable uneveneess of a surface. Numerous parameters and norms used to create quantified descriptions of surface roughness were defined in subject literature and norms. However, two of them are most frequently used [11], [12].

Ra – meanarithmetic deviation of surface roughness profile forming the average line, which is the average value of distance between points y1, y2,...yn on the observed profile from the average line on the measured section (5).

$$Ra = \frac{1}{n}\sum_{i=1}^{i=n}|y_i| \qquad (5)$$

Rz – difference between arithmetic mean hight of the five highest peaks and arithmetic mean depth of the five deepest valleys in regard to average line on the length of the measured distance (roughness based on 10 points on the profile) (6).

$$Rz = \frac{1}{5}[(R_1 + R_3 + R_5 + R_7 + R_9) + (R_2 + R_4 + R_6 + R_8 + R_{10})] \qquad (6)$$

The following characteristics of those parameters have to be noted:

Ra – Reacts weakly to local changes and its values do not provide a clear image of the surface condition.

Rz – also known as the "profile's biggest height" – can be used for the majority of surfaces.

Changes of parameters in the compared fragments of scans performed in subsequent periods may indicate, among others, erosion of concrete surface, increase in dampness or change in texture due to plant overgrowth. Expected, important (influencing structure work and safety) size of the changes in the evaluated surfaces (e.g. cracks, chipping, heavy soiling by, for example, plant overgrowth, outflow and deposition of calcium carbonate on the surface) can be identified as changes in range of 0,5-10 cm on the selected uniform areas with surface above 1 m. Because of that, roughness parameters are specified in milliliters and centimeters and not, as in the previously quoted sources, in micrometers. Accuracy of distance measurement using a laser scanner, considering that the average of the result on a surface and laser spot is estimated at 3mm +1ppm, is satisfactory when identifying sizes being the point of interest for the authors. Surface roughness parameters were identified for the scanned hydrotechnical concrete samples. Samples were scanned using Z+F Imager 5006h in three resolutions: "middle", "high" and "ultra high" with "scan quality" set to "high". A fragment of point cloud representing a single surface of a cubic sample was selected for calculations. Ra and Rz parameters were calculated in millimetres using orthogonal regression's best-fitting line integrated into a point cloud projected on a horizontal plane as a middle line. This simplification was possible because the cubic concrete sample was placed in such a way, that its vertical edges were parallel to the scan's OX axis and perpendicular to the laser scanner's horizontal line of sight. Because roughness parameters are dependent on the selected scan resolution, table 3 presents values of the obtained resolution depending on the scanners operational mode. Table 4 summarises the obtained Ra and Rz values for surface A of the concrete sample using the given setting.

Table 3. Dependence of scan resolution on Z+F Imager 5006h scanner's operational mode – distance between neighbouring points [mm] (beam's angle of incidence 0°, D – distance from the scanner [m]

Operational mode	„ultra high"	„high"	„middle"
D [m]	Resolution[mm]		
10	1,6	6,3	12,6
20	3,2	12,6	25,2

Table 4. Summary of Ra and Rz values for surface A of the concrete sample (resolution m –"middle", h – "high", u – "ultra high")

Beam's angle of incidence [°]	Resolution	Ra [mm]	Rz [mm]	Number of points
34	m	3,39	10,47	21
	h	1,08	7,44	97
	u	1,07	15,94	1523
40	m	5,36	20,61	28
	h	1,04	5,96	89
	u	1,06	24,25	1405
44	m	2,79	7,95	18
	h	0,69	3,46	74
	u	1,18	14,34	1297
60	m	3,55	7,14	12
	h	1,26	5,29	59
	u	0,97	7,97	943

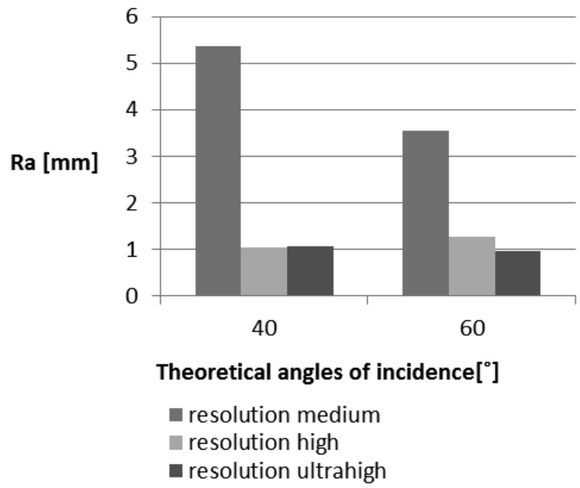

Figure 4. Ra parameter values for the selected concrete sample surface with beam's angle of incidence equal to 40° and 60°

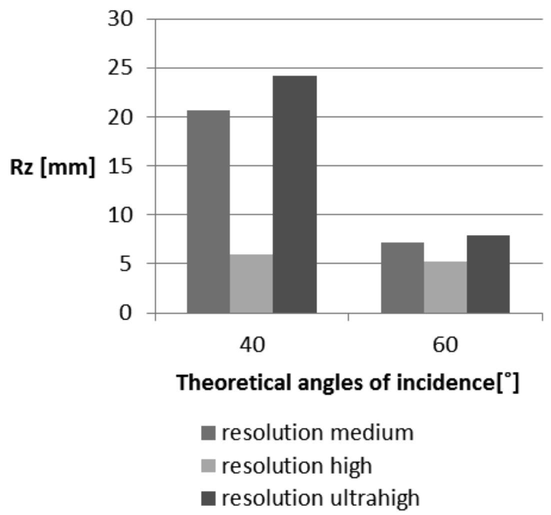

Figure 5. Rz parameter values for the selected concrete sample surface with beam's angle of incidence equal to 40° and 60°

For the "middle" resolution, the value of the roughness parameter deviates significantly. This is caused by imprecise capture of the surface on the point cloud. The distance between registered points is big enough to cause disruption in actual roughness. This effect is not present when resolution is set to "high" and "ultra high" as more points are being recorded. For "high" and "ultra high" resolutions and angles of incidence at 34° and 40° Ra parameter is equal at 0,02mm, whereas for angles of incidence at 44° and 60° the discrepancy reaches 0,49 mm and 0,29 mm respectively (table 4). Rz parameter variability takes on a completely different character than Ra variability. Rz values for an identical sample scanned using different angles of incidence are most convergent when resolution is set to "high". These dependencies can be observed on the following graphs (fig. 4 and 5).

Conclusions

A simple procedure is required when identifying a beam's angle of incidence. Knowing the parameters of the equation for orthogonal regression line and the equation for the line crossing the centre of the instrument and the centre of the analysed surface, it is possible to identify the angle of intersection of those lines, thereby identifying the beam's angle of incidence on the selected fragment of the point cloud. Parameters of the equation for the orthogonal regression line can describe geometrical characteristics of single surfaces extracted from the point cloud. It is essential to determine the laser beam's angle of incidence and surface inclination angle when preparing data required for classification of the surveyed surface in order to identify areas with diverse concrete surface properties. Knowledge of those angles allows for taking into account the registered reflected beam's Intensity value resulting from geometrical conditions of the measurement and for data analysis unencumbered by the geometry of the recorded scene. Dependencies of the recorded Intensity value on the beam's angle of incidence and the distance from the object described in [2], [13] and [14] indicate how important it is to determine the beam's angle of incidence and surface inclination angle when preparing data for TLS surface condition analyses.

Knowledge of the coefficients describing roughness or harshness of a concrete surface is very important for a set of reasons. Roughness has a significant influence on the speed of erosion and plant overgrowth. When downstream side was constructed with significant longitudinal slides, roughness contributes to an increase in undesired phenomena.

At present, roughness parameters are not taken into consideration when evaluating concrete surface condition – employed contact-free video methods based on direct observations and analysis of surface pictures do not provide the data for calculations. Their results are only grounds for the issuing of a general descriptive evaluation. No mention suggesting a change in the currently used methods of assessment was found in the subject literature. Application of the analysis of TLS point cloud with the use of simple orthogonal regression algorithm suggested in the article allows for a reliable assessment of surface erosion.

Accuracy of the visualisation of the surface and roughness parameters, in particular Ra (mean arithmetic deviation of surface roughness profile forming the average line) are closely correlated to scan's resolution of the surveyed area. Presented analyses indicate a need to identify areas with uniform visualisation [2] in the compared scans. Evaluation of the surface condition is required under law for numerous concrete engineering structures. Water Law [13] imposes mandatory control of the condition of structures like concrete dams and concrete weirs that are a part of an earth dam. Changes in surface roughness may indicate erosion. Comparison of roughness parameters calculated after each control check may serve as one of the elements of evaluation of surface technical condition and may indicate concrete erosion and a need to apply additional protective measures like cleaning, covering the surface with protective agent and, in some cases, even repair processing by grinding and filling of cavities.

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