Towards the Influence of the Angle of Incidence and the Surface Roughness on Distances in Terrestrial Laser Scanning

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SUMMARY

Terrestrial laser scanner allow nowadays the determination of changes of the structure's geometry with millimetre accuracy. To ensure the achievement of this accuracy level it is necessary to account for systematic deviations, as they can cause apparent deformations or rigid body movements.

The errors of the reflectorless distance measurement have an essential contribution to the error budget of terrestrial laser scanner measurements. In the major part of current research these errors are obtained by means of deviations from approximating surfaces. In contrast to this, we present in this contribution an approach to obtain the systematic errors of single measured distances. It is based on the direct comparison of a scanned distance with a reference distance. The basis for the determination of the reference distances is a high-accuracy geodetic network that extends over the entire range of the measured distance. The starting point of the reference distance corresponds to the station of the terrestrial laser scanner. Its coordinates are determined by resection from the network points. The endpoint of the reference distance is determined by industrial measurement techniques from a high-accuracy point cloud.

The approach is used to study the impact of the angle of incidence on scanned distances. Based on the obtained results we discuss two perspectives on the influence of the angle of incidence. In the global perspective, adopted up to now in most research, the angle of incidence is the angle between the laser beam and the approximated surface. The presented results additionally sustain a local perspective on the angle of incidence as an angle between single rays of the laser beam with particles of the rough surface. The two perspectives are compared with respect to their relevance for the assessment of systematic deviations of scanned distances under special consideration and quantification of the surface roughness.

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1. INTRODUCTION

Terrestrial Laser Scanner (TLS) enable the acquisition of a structure's geometry from a distance of several meters with millimetre accuracy. In this context, there is a need to account for systematic deviations of the measurements, as they have a one-sided influence on the measured quantities and thus, can cause apparent object deformations, rigid body movements or a combination of both. The deviations occurring in the reflectorless distance measurement have a main contribution to the total error budget of terrestrial laser scanning results. The angle of incidence (AOI) has an important influence on the reflectorless distance measurement. It is traditionally defined as the angle between the measuring beam and the local normal to the surface.

However, at the differential level of the interaction between laser beam and the object's surface several AOI result i.e. between every single ray of the beam and the corresponding normal to the surface under consideration of its local "wiggles" occurring due to roughness (see Fig. 1). The mean of these AOIs may differ from the traditionally defined AOI, thus causing different deviations of the distance measurement. This point of view supports the hypothesis, that instead of a single influence due to the AOI a combined effect of the AOI and the surface's roughness may influence the distance measurement. This paper aims to investigate this alternative perspective.

So far, different strategies were applied for studying and quantifying the effect of the AOI on the reflectorless measurements. Lindstaedt et al. (2009) analyse the variation of the distance between a scanned surface and a reference plane with the AOI. Soudarissanane et al. (2011) use the standard deviation of the distance residuals to an adjusted plane to emphasize the influence of the AOI. Gordon (2008) considers the variation of the 3D-point accuracy with the AOI. Common to all approaches is the use of an approximated surface, which implies assumptions on the geometric form of the scanned object. If these assumptions do not hold, they distort the quantification result.

Different to the abovementioned approaches, our approach focuses on single scanned distances and relates them to reference distances. The deviations between them are used to assess the influence. To verify the hypothesis of a combined influence, the differences are quantified under different AOI and for surfaces of different roughness levels. To date, the approach is developed for scanning total stations (TLS+TS). However, the adaption to TLS is straightforward and will be content of future research.

The novel approach as well as the obtained results are described in this paper using the following structure: The second Chapter describes the framework of the study. The performed investigations are describes in the third Chapter. Obtained results and following interpretations are given in the fourth Chapter. This paper is a synopsis of Zámečníková and Neuner (2017).

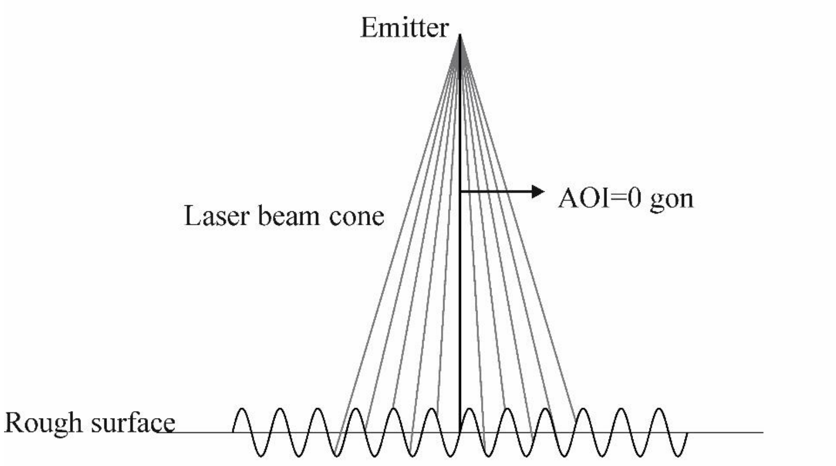

Fig. 1: The traditional definition of the AOI and the motivation for a different perspective on a combined influence due to AOI and roughness.

2. FRAMEWORK OF THE STUDY

The investigated distances D_{TLS} are measured in scanning mode and are regarded as distances between the TLS+TS'origin and the object point corresponding to the 3D-coordinates listed in the output file. Allocated to these distances are the horizontal direction Hz_{TLS} and the vertical angle V_{TLS} , which are obtained from the same coordinate-triple. The used TLS+TS is the Leica MS 50. This TLS+TS fuse the scanning system and the total station system into a single instrument. Thus, the measurement results obtained with the two technologies refer to the same instrument's coordinate system. The accuracy of the distance measurement is specified with 2 mm + 2 ppm and the angle accuracy with 0.3 mgon.

To analyse the effect of the AOI and of the roughness on scanned distances these parameters were varied as follows:

- Modification of the AOI by rotating the analysed object with respect to its almost vertical axis and aligning it to an analogue angular scale. With regard to its dimensions, we can assume that in a certain rotated position the same AOI (regarded in the traditional sense) occurs for all points.
- Modification of the roughness by using three granite plates coming from the same granite block and prepared by different methodologies to exhibit different roughness levels. These levels are referred by the qualitative nomenclature “smooth” (S), “rough” (R) and “very rough” (VR). Although the used close range scanner (see below) allows for a quantification of certain roughness parameters conforming to the DIN EN ISO 4287 2010/2013 the indication of roughness levels is preferred here in order to maintain the focus on the general possibility of a combined influence due to AOI and roughness. If this hypothesis is confirmed, the roughness will be quantified precisely.

A dominant influence of the AOI is expected for the smooth surface while the combined influence can particularly occur for the rough and the very rough surface under different AOIs.

All measurements were performed under lab conditions. The TLS+TS was placed at a range of 10 m to the granite plates, thus avoiding close-range effects. A low scanning frequency of 62 Hz was chosen to keep the measuring noise at the lowest possible level. The point density of the scanned surface was 1 cm.

3. INVESTIGATION OF INFLUENCES DUE TO AOI AND ROUGHNESS

The difference between D_{TLS} and a corresponding reference distance is used to assess a possible combined influence due to AOI and roughness. For each configured AOI the approach allows to obtain several differences between scanned and reference distances. Subsequently, these differences are averaged to reduce stochastic influences.

3.1 Determination of the reference distance D_{ref}

A reference distance D_{ref} is obtained from separate determinations of the coordinates of its starting and end-point. The starting point corresponds to the origin of the TLS+TS and is common to all D_{ref} . The determination of D_{ref} comprises three steps:

- determination of a high-accuracy geodetic network,
- determination of the starting point,
- determination of the endpoint.

Fig. 2 shows the adopted measuring configuration.

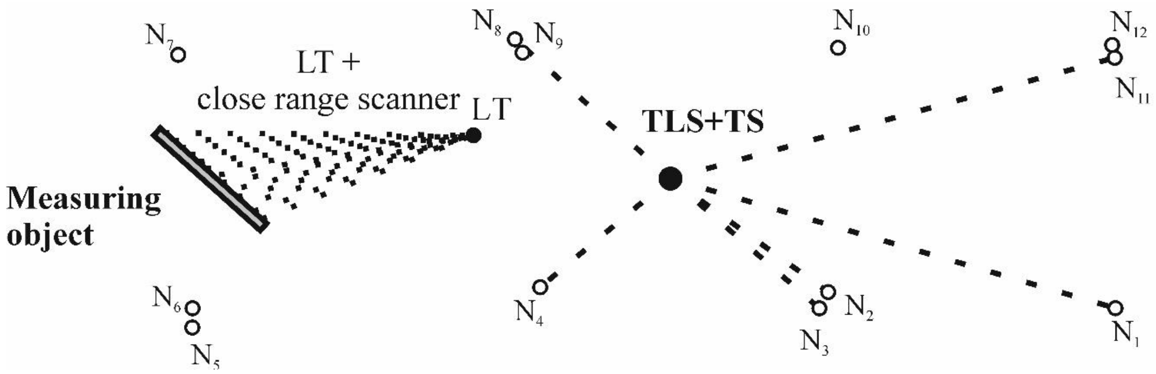

Fig. 2: Measuring configuration

The high-accuracy geodetic network was implemented in the lab and has a spatial expansion that exceeds the ranges considered in this paper. Therefore, only a subset of the network points, denoted by N_1 to N_{12}, was used. The measurements were performed with the laser tracker Leica AT 960 (LT), which has a specification of the maximum permissible error (corresponding to the uncertainty of a point coordinate) of 15 µm + 6 µm/m. The instrument's residual inclination was recorded enabling to reference of the measurements to the gravity.

The Unified Spatial Metrology Network (USMN)-function of the Spatial Analyzer software was used to obtain the coordinates of the network points. Their a posteriori standard deviation is below 0.06 mm. The adjusted coordinates of the network points introduce a reference frame as a realisation of the coordinate system $Y_{ref}, X_{ref}, Z_{ref}$.

The reference distance's starting point was determined by resection and trigonometric levelling using the network points closest to the instrument's station. The used CCR is particularly suited for manual close range targeting. This allows complying with the nominal angular accuracy of the instrument. Based on error-free network points, the obtained standard deviation of a coordinate of the TLS+TS origin is below 0.02 mm.

The endpoints of the reference distances were determined separately for every surface and every configured AOI using a close range scanner of type Leica LAS-20-8 with an uncertainty of spatial length UL = 60 µm if under 8.5 m (HEXAGON 2017). This allows the acquisition with a point density of 0.02 mm. As the LT determines the position and the orientation of the close range scanner during the measurements, the resulting point cloud is in the reference coordinate system Y_{ref}, X_{ref}, Z_{ref}. To distinguish the resulting point cloud from the one obtained by TLS+TS it will be denoted subsequently as the reference point cloud.

The reference distances D_{ref_i} are obtained from the coordinates of the starting point (Y_{ref_P0}, X_{ref_P0}, Z_{ref_P0}) as well as the coordinates of the reference point cloud P_i (Y_{ref_i}, X_{ref_i}, Z_{ref_i}). Allocated to these distances are the horizontal directions Hz_{ref_i} and the vertical angles V_{ref_i} , which are obtained from the same coordinate-triple. Thus, the reference directions and angles are related to the corresponding axis of the reference coordinate system X_{ref} and Z_{ref} respectively. The accuracy of the reference distances needs to be at least one order of magnitude higher than the accuracy of D_{TLS}. A thorough analysis of possible error influences on the determined reference distances revealed that their standard deviation is even for the most unfavourable configuration below 0.2 mm (see also Zámečníková and Neuner, 2017 for further details).

3.2 Determination of the deviation of the scanned distance D_{TLS}

Maintaining the same position of the measuring object as in the case of the close range scanning a subsample of its surface with dimensions of 20x15 cm is scanned with the TLS+TS. The following 19 AOI were configured for each granite plate: (0, ± (10, 20, 30, 35, 40, 45, 50, 55, 60) gon). Positive AOIs correspond to clockwise rotations of the granite plate while negative AOIs correspond to counter-clockwise rotations respectively.

As mentioned in the second chapter the polar elements D_{TLS}, Hz_{TLS} and V_{TLS} are obtained from the coordinate triples of the TLS+TS point cloud. Obviously, the polar elements refer to the instrumental coordinate system. To allocate D_{TLS} to D_{ref} it is necessary to express the corresponding Hz and V in the same coordinate system, i.e. the reference coordinate system. As both coordinate systems are oriented to gravity due to levelling of the LT and the TLS+TS the comparability of the V-angles is straightforward. The angle OU between the zero-axes of the horizontal directions Hz_{TLS} and Hz_{ref_i} results from the resection, applied to obtain the coordinates of the starting point. The standard deviation of the estimated OU is 0.06 mgon.

By applying the OU to the horizontal directions Hz_{TLS_i} one obtains $Hz_{TLS\_i\_ref}$. This enables the identification of identities between spatial directions ($Hz_{TLS\_i\_ref}$, $V_{TLS\_i\_ref}$) and the reference spatial directions (Hz_{ref_i}, V_{ref_i}) and thus, correspondent D_{TLS} and D_{ref} distances. Despite the high sampling rate of the close range laser scanner, these identities occur only in exceptional cases. Therefore, a search domain of the form

$$Hz_{TLS\_i\_ref} - \Delta Hz \leq Hz_{ref\_i} \leq Hz_{TLS\_i\_ref} + \Delta Hz \, , \qquad (1)$$

$$V_{TLS\_i\_ref} - \Delta V \leq V_{ref\_i} \leq V_{TLS\_i\_ref} + \Delta V \, , \qquad (2)$$

is applied, in order to identify the correspondences. ΔHz and ΔV are permissible angular deviations from $Hz_{TLS\_i\_ref}$ and $V_{TLS\_i\_ref}$ and are set to 0.3 mgon in this study. The maximal impact of these deviations on D_{ref} is 0.06 mm. With this approach between 140 and 290 correspondent distances could be identified for every configured AOI. The differences between correspondent reference distances and scanned distances are calculated and averaged to ΔD_m for every AOI, in order to reduce the stochastic effects on the quantified influence. Additionally to the mean value ΔD_m, the standard deviation of the differences was calculated on an AOI basis as well.

The mean values ΔD_m can be influenced by the eccentricity between collimation axis and the reflectorless distance measurement axis of the TLS+TS as well as by systematic deviations of the estimated *OU*. Both influences are angles that have the same geometric effect on the reflectorless distance measurement as the AOI. However, different to the AOI, these effects cancels when averaging the mean differences obtained for the same AOI by clockwise and counter-clockwise rotation. Therefore, the representative deviations for the further analysis are:

$$\Delta D = \frac{\Delta D_{m,+AOI} + \Delta D_{m,-AOI}}{2} \, , \qquad (3)$$

with the corresponding standard deviation:

$$\sigma_{\Delta D} = \sqrt{\frac{\sigma_{\Delta Dm,+AOI}{}^{2} + \sigma_{\Delta Dm,-AOI}{}^{2}}{4}} \, . \qquad (4)$$

Repeated measurements to the points of the reference network furnish the evidence on the stability of the TLS+TS and of the LT during the campaign. The stability of the network points was proofed by independent network determinations before and after the campaign.

4. RESULTS AND INTERPRETATION

The combined influence of the AOI and of the roughness reveals from the variation of the ΔD with the AOI for the three granite plates of different roughness level. The according curves are shown in Fig. 3a and the corresponding standard deviations in Fig. 3b.

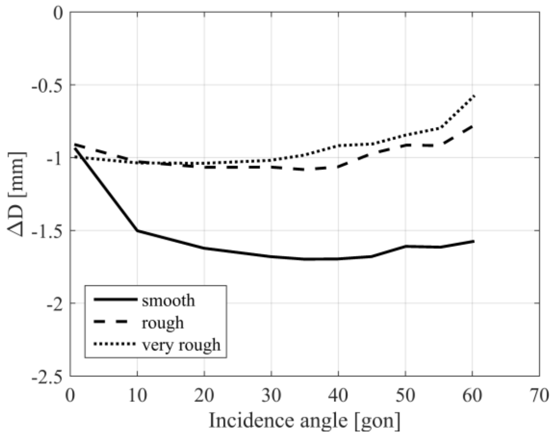

Fig. 3a: Deviations between reference and scanned distances under different AOIs for three granite plates of different roughness level

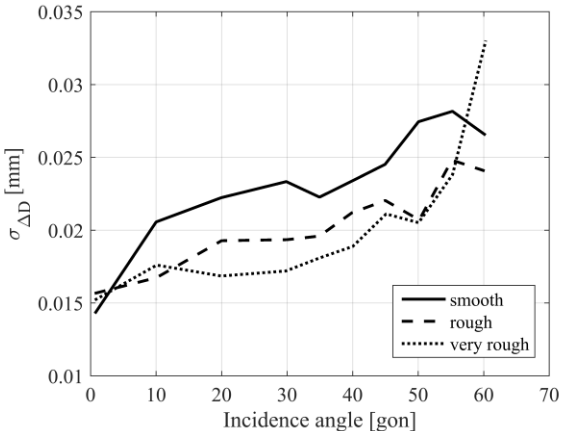

Fig. 3b: Corresponding standard deviations

The course of ΔD for the smooth granite plate is due to its low roughness level mainly determined by the AOI. As expected, the best match between scanned and reference distance is at AOI = 0 gon. The absolute value of the deviation increases for AOIs up to 20 gon and keeps a mainly constant level for AOI between 20 and 60 gon. The total variation of the deviation is 0.76 mm. Increased AOIs lead to longer scanned distances D_{TLS}.

Different to the smooth granite plate, for the rough and the very rough plate the ΔD has a constant level for AOIs between 0 gon and 40 gon. The absolute value of the deviations decreases between 40 gon and 60 gon. The total variation is of 0.30 mm for the rough granite plate and of 0.47 mm for the very rough granite plate respectively.

The relevance of the formulated hypothesis of a combined influence of the AOI and of the roughness on the scanned distances follows from the comparison of the ΔD courses obtained for the three granite plates. The differences vary up to 0.79 mm (S-R: between 0.02 mm and 0.79 mm; S-VR: between -0.06 and 1.00 mm; R-VR: between -0.09 and 0.21 mm). The necessity of a combined treatment of AOI and roughness was proven by statistical significance tests, performed with a significance level of 95%. The null- and alternative hypothesis are:

$$\begin{aligned} & H_0 : E(d_i) = 0 \\ & H_A : E(|d_i|) > 0 \text{'} \end{aligned} \qquad (5)$$

whereby d_i are the differences between the deviations ΔD, obtained for the same AOI at different plates. Corresponding standard deviations were obtained from the standard deviations given in Fig. 3b.

The test results indicate significant differences between the deviations. Few exceptions occur for AOI = 0 gon between S-R and S-VR as well as for AOI = 10 gon and 20 gon between R-VR. These results confirm the hypothesis of a common influence of the AOI and of the roughness on the scanned distances.

5. CONCLUSIONS

This paper reports on measurements and processing steps performed to quantify systematic distance deviations of a TLS+TS. The used method is based on the comparison of single measured distances with corresponding reference distances. In present, the method applies to scanning total stations. However, replacing the CCR by TLS-targets allows its transfer to typical TLS systems.

The combined influence of AOI and roughness on the scanned distances was examined with an TLS+TS for a distance of 10 m and for granite plates of three different roughness level. A systematic characteristic of this influence was found out. The absolute value of the deviations increase for the S-surface between 0 gon and 20 gon, and holds a constant level beyond this AOI. Different to that, the absolute value of the deviations remains on a constant level for AOI up to 40 gon for the R and VR surface, and decreases beyond this AOI. The quantified total variation of D_{TLS} under the influence of the AOI and the roughness is maximum 0.8 mm.

It should be stressed, that the results of this research are so far restricted to the framework of this study. A general statement on the combined influence of the AOI and the roughness on scanned distances requires a variation of at least the instrument type, the parameters of the analysed surfaces (e.g. material, roughness) as well as the ranges. This will be content of near future work.

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