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Original Research Article

EMPIRICAL ANALYSIS OF THE ACCURACY OF PULSED LASER SCANNERS UNDER DIFFERENT MEASUREMENT CONDITIONS

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A b s r a c t

Terrestrial laser scanning is becoming increasingly widely used in engineering surveying, especially in the area of displacement monitoring and performing diagnostic measurements. Empirical assessment of laser scanner accuracy in real measurement conditions is of great importance when it comes to assessing the suitability of scanners for specific engineering applications. This paper describes an empirical analysis of the accuracy of two pulsed laser scanners: Leica ScanStation C10 and Riegl VZ-400i. The tests were conducted in two measurement environments: inside and outside a building, where test bases were designed and made in the form of a set of several reference points, i.e. reflective targets. During the tests, the deviations of spatial distances, spatial angles and coordinates were analysed on the basis of the results of scanner measurements in relation to precise total station measurements treated as reference. Additionally, the accuracy of the reference sphere approximation was tested. The results obtained indicate that the values of spatial distance deviations between pairs of targets for measurements performed inside the building are comparable for both scanners. The mean absolute error (*MAE*) was 1.6 mm for the Leica scanner and 1.9 mm for the Riegl scanner. For measurements outside the building, the Leica scanner proved to be more accurate. The *MAE* of spatial angle deviations between targets for measurements inside the building was 54^{cc} for the Leica scanner and 96^{cc} for the Riegl scanner, while outside the building, it was 29^{cc} for the Leica scanner and 73^{cc} for the Riegl scanner. The average error in matching the local scanner system with the reference coordinates inside the building was 0.9 mm for the Leica scanner and 1.3 mm for the Riegl scanner, and outside, it was 0.8 mm for the Leica scanner and 2.5 mm for the Riegl scanner. Additionally, the accuracy of the reference sphere approximation was tested. The analyses carried out prove that even an older scanner model (ScanStation C10) has high measurement accuracy useful in engineering surveying despite the significantly slower measurement compared to modern scanner models.

Keywords: terrestrial laser scanning precise total station, statistical data analysis, deviation of distances, angles, and coordinates, approximation of reference spheres

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1. INTRODUCTION

Laser scanners are currently increasingly used in engineering surveying, both in the context of inventory and diagnostic measurements, as well as in measurements of displacements and deformations. Depending on the type of work performed, attention should be paid to the required accuracy. Accuracy tests of devices conducted under laboratory conditions can provide a lot of valuable information, but do not always reflect the accuracy that can be realistically obtained in real field conditions.. Considering the use of a scanner for a specific surveying work, one should be aware of its technical capabilities (e.g. measurement range) and limitations, e.g. field of view, that is those impacting its measurement accuracy. In the context of the accuracy obtained, the technological development of new models of laser scanners supplied to the market is not without significance here. Regarding the potential applications of laser scanners, it is crucial to emphasise their important role, for example, in architectural and construction inventories, and in surface flatness control. Thanks to the ability to precisely map the geometry of objects and analyse their shapes in high resolution, laser scanners are becoming an indispensable tool in documenting the technical condition of buildings. In the case of diagnostic measurements, the accuracy achieved at the millimetre level is crucial to meeting technical requirements and industry standards.

The testing methodology of laser scanners is described in the international standard ISO 17123-9:2018 [1] which in both simplified and full field procedures involves using of a measurement base consisting of two scanner positions and four target marks. The assessment of the scanner accuracy in this method is based on matching the target centres in dedicated software and then, based on their coordinates, calculating the spatial distances. Different approaches to testing the performance of 3D-imaging systems, including laser scanners, are described in two ASTM standards. The standard ASTM E2938-15 [2] provides an evaluation of the relative error in measuring the distance of a laser scanner between two flat targets. The standard evaluates the performance of the scanner in a range of 2 to 150 m and allows testing of a variety of target materials. More extensive scanner performance test procedures, including two-face tests and point-to-point distance tests, are described in the standard ASTM E3125-17[3]. Both standards recommend the use of a more accurate measurement instrument to provide reference data.

Testing the accuracy of laser scanners is an issue widely described in the scientific literature. In laser scanning, it is important that the result obtained faithfully reflect reality. This includes correct representation of distances between scanned objects. This is important when checking the dimensions and shape of scanned objects, e.g. during an as-built inventory of a building. A typical procedure for distance checking described in the literature is the use of a precise total station or the so-called laser tracker as a reference instrument. Reference data are collected in several measurement series and allow for a detailed analysis of errors, including the identification of systematic errors. Tests can be performed outdoors and in a laboratory where the influence of weather conditions is minimised. In field measurements, it is necessary to take into account the variable influence of weather conditions, such as amount of sunlight, pressure, air temperature, rain, fog, humidity, or device temperature, all of which can affect the propagation of the laser beam [4–8]. Additionally, the intensity of reflection on different surfaces is tested. In particular, on smooth surfaces, which may become a cause of an increase in the intensity of reflection and anomalies in the distance data, which, in turn, can decrease the accuracy of measurements [9, 10]. An alternative method of testing distances is to use the laser scanner itself to calibrate a network of reference points, known as self-calibration. In this method, instead of using a higher accuracy device (e.g. a laser tracker), the laser scanner measures selected stationary targets from many different positions. Then, the network method is used, which involves averaging the results and reducing systematic errors by adjusting the scanner error model. Thanks to this method, the scanner can create a reference system to test its accuracy. A key step is to adjust the TLS error model, which takes into account various sources of uncertainty, such as beam offset, angular errors, or inconsistency in distance readings. This process allows for a significant reduction in systematic errors, and as a result, more reliable measurement results [11].

The second aspect commonly checked is the analysis of angular accuracy which can be performed in several ways. One of them comparison of the angle values calculated between the scanned objects with reference angles. This method verifies whether the point cloud obtained from the scanner correctly maps the space in terms of angles. The reference data should come from measurements with a higher precision and accuracy than those offered by the tested laser scanners [7, 8]. The second method of angle analysis described in the literature is the comparison of measured angles, where a scanner position is the vertex of the angle. For this purpose, chosen points distributed evenly around the scanner are scanned, after which a measurement is performed from the same position with a usage of a precise total station or a so-called laser tracker. It is important that the height of both instruments (the scanner and total station) at this position should be the same. Such setting will facilitate a precise comparison of the measurements [7–9, 12]. This will eliminate the influence of the inclination error (lack of perpendicularity of the axis of rotation of the total station telescope or the rotating prism of the scanner to the main vertical axis of rotation of the instrument) [7, 9].

The third important parameter tested is the resolution of the laser scanners. This parameter consists of angular increments and the size of the laser spot, both of which affect the accuracy of distance measurement and the resulting number of scanned points. A larger number of points allows for better reproduction of surface details of objects, due to which a model of the object can be made with higher accuracy. In the tests, various complex objects are used, e.g. boxes with increasingly narrower slots directed towards its centre. When such box is placed perpendicularly to the scanner and scans are performed in different resolution configurations, the number of points on the back wall and their arrangement near the centre are analysed, which allows for assessing the scanner's ability to reproduce details [13, 14]. Alternatively, resolution can be tested by checking the scanner's range in detecting reflective targets set at various known distances. The targets are set stably at known distances from the scanner and then a series of scans are performed with different resolution settings. The scanner then detects the farthest target from its position. This allows an assessment of the effect of resolution on the scanner's ability to work at different distances, which is important in scanning hard-to-reach objects [13, 15]. An additional factor that influences the accuracy of the measurements is the orientation of the scanned object relative to the scanner. In cases of some measurement marks, such as contrasting targets, their position can affect the precision of determining the object's centre. Changing the target’s angle relative to the scanner can cause slight shifts in the centre determined in the point cloud. This effect results from the limited angular resolution of the scanner and the way in which data are processed from high-contrast surfaces [16].

The study of the accuracy of scanning geometric solids is an important method for assessing scanners' ability to model three-dimensional space. Using this method, it is possible to determine how well the scanners can cope with mapping regular and irregular solids that are often found within the scanned space. This information is very valuable to both manufacturers and users, and plays an important role, among others, in modelling of existing piping systems [13, 17]. Various methods for analysing the correctness of scanning solids in terms of reflecting the actual shape have been described in the literature. One of them is comparing the dimensions of the scanned solids with the solids’ actual dimensions. Such analysis can also be enriched by comparing the volume of solids calculated on the basis of data from the laser scanner with reference data. A difficulty that may arise in using this method may be precise determination of the exact dimensions of the irregular solids used in the study [6, 13]. The second approach to this analysis is checking the scanner's ability to precisely determine the object's centre of gravity. For this purpose, a series of measurements are performed with a laser scanner, and then the position of the body's centre of gravity is estimated in the software using numerical methods. The repeatability of the position of the centre of the same body on each scan is then analysed, or the detected centre of gravity is compared with its actual position [13, 17].

In surveying practice, a question often arises whether technological progress in new models of laser scanners actually translates into better data quality and greater measurement accuracy. Can older devices still provide sufficient accuracy in specific measurement conditions? In addition, due to the wide range of potential scanner applications, it is important to determine how they perform in different working environments. This applies to both indoor measurements, where steep sight lines of varying lengths and reflections from shiny elements may occur, and outdoors, where atmospheric conditions may have a greater impact. The above premises motivated the authors of this paper to test two models of pulse laser scanners (a scanner made several years ago and a modern model from another manufacturer) in real measurement conditions inside and outside the building, in order to empirically examine the accuracy of these scanners in the context of practical geodetic applications. Differing from ISO standard [1], the authors decided to increase the number of targets to better represent real measurement conditions (when the targets are available at different angles and distances from the scanner). This approach allows for a more comprehensive analysis of the impact of scanning geometry on the accuracy of the results. An original element of the work is also the analysis of the possibility of using measurement spheres in combination with the Riegl scanner, which is not adapted to use these types of signs. The results of the research can serve as useful guidance for surveyors, engineers, and other specialists who are faced with the choice of the right scanner for specific measurement tasks.

2. METHODS

2.1. Characteristics of the tested scanners

In this paper, the authors tested two pulsed laser scanners: Leica ScanStation C10 (hereafter referred to as Leica) and Riegl VZ-400i (hereafter referred to as Riegl). The choice of these laser scanners for this study was made primarily according to the stated research objective, which was to answer the question: Can older devices still provide sufficient accuracy in specific measurement conditions? The Leica scanner is the oldest model available at the Faculty. The Riegl scanner is a representative of the new generation of scanners with multi-target capability (4-15 objects detected from one laser pulse). Both scanners are used at the Faculty for scientific research and commercial work; therefore, the tests performed can help verify their accuracy and can help other surveyors in similar tests. The Leica is an older generation scanner equipped with a box level, a two-axis compensator, and an integrated RGB camera, which semi-automatically detects, among others, black and white round "chequerboard" targets and reference spheres. Similarly to a total station, the Leica scanner has a replaceable tribrach that allows precise centring and levelling of the instrument over a geodetic point and georeferencing scanner using the traverse or resection method. The Riegl scanner is a much newer model, with an external RGB camera, it does not require manual levelling and is equipped with an integrated 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer (compass). This scanner fully automatically detects round, flat reflective targets, and the class-1 laser allows safe measurement for random passers-by, making field work much faster and easier. The comparison of the basic parameters of both scanners and the Trimble S3 robotic total station which was used as the reference instrument is presented in Table 1.

Table 1. Specification of the total station and laser scanners examined

Parameters	**Leica ScanStation C-10**	**Riegl VZ-400i**	**Trimble S3 (total station)**
Laser beam length	532 nm (green)	near infrared	660 nm
Laser class	3R	1	3R for direct reflex (DR), 1 for prism mode
Maximum measurement range	300 m	800 m for 100 kHz* 250 m for 1200 kHz*	2,500 m for 1 prism, >500 m for reflective foil
Maximum scanning speed	50 000 pts/s	500 000 pts/s	n/a
Accuracy of a single measurement			
3D position accuracy (at a distance of 50 m)	6 mm	3 mm	n/a
Ranging accuracy (at a distance of 50 m)	4 mm	n/a	2.1 mm in prism mode 3.1 in DR mode
Ranging precision (at a distance of 100 m)	n/a	5 mm	2.2 mm in prism mode 3.2 in DR mode
Vertical angle**	37^{cc}	31^{cc}	6^{cc}
Horizontal angle**	37^{cc}	31^{cc}	6^{cc}

n/a - not applicable or not available in manufacturer's specifications
* laser pulse repetition rate (rounded values)
** angular unit 1^{cc} = 0.0001 grad = 1.5708 μrad

In order to reliably evaluate the accuracy of the tested scanners in various measurement environments, the authors designed two test bases, the first located inside and the second outside the building of the Wrocław University of Science and Technology.

2.2. Test base located inside the building

The test base located inside the building consisted of 15 specially designed measurement marks. Each mark had two targets. On the left side, there was a black-and-white “chequerboard” printed with a diameter of 5 cm, marked with the prefix “L”, and was to be used with the Leica scanner. On the right side, there was a second round target with a diameter of 5 cm, cut from SurvGeo reflective foil, marked with the prefix “R”, and dedicated to the Riegl scanner (Fig. 1).

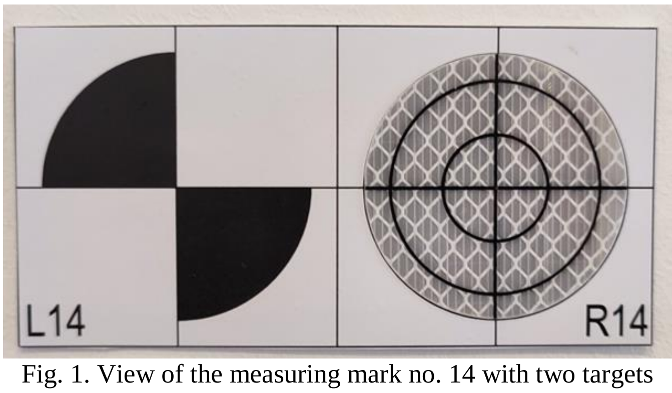

Fig. 1. View of the measuring mark no. 14 with two targets

Then the prepared measurement marks were placed in the hall of the building (Fig. 2) on the walls, columns, and window frames at different heights (measurement marks Nos. 1-11) and at a fixed (equal) height (measurement marks Nos. 12-15). Furthermore, three Survpoint reference spheres were prepared and attached to a special stand (Fig. 3). This ensured that a constant mutual distance between the spheres was maintained during the measurement, while the distance of the stand with the spheres from the scanner position could be changed.

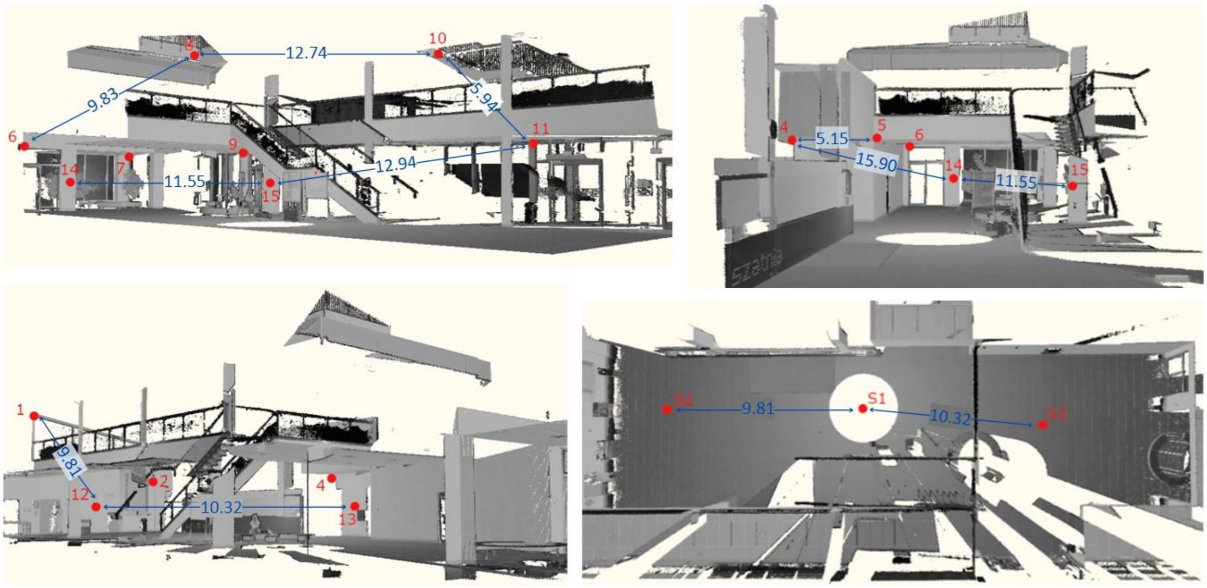

Fig. 2. Arrangement of measurement marks and instrument positions inside the building (dimensions are given in meters)

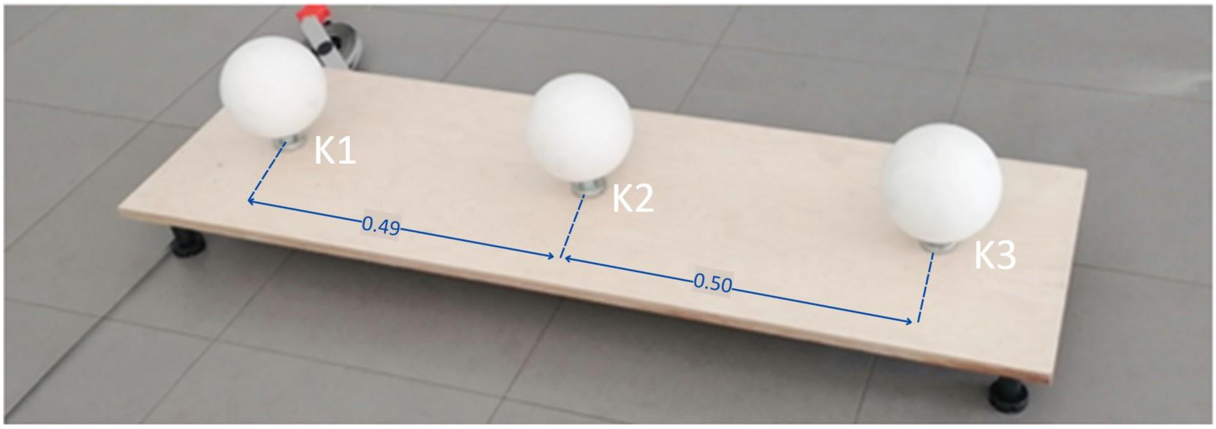

Fig. 3. View of the reference spheres on the stand (dimensions are given in meters)

The total station measurements were taken from three positions (S1-S3) located non-collinearly (Fig. 2). At each position, measurements of vertical and horizontal angles and spatial distances were taken in three series, aimed at the visible measurement targets and neighbouring instrument stations. Measurements were then taken with the Leica scanner only from S1 position, whereby visible targets were scanned in three measurement series. Additionally, a stand with three reference spheres was scanned, which was arranged successively at distances of 3 m, 6 m, 9 m, 12 m, and 15 m from the scanner. Analogous measurements were taken with the Riegl scanner, but due to faster measurement, the targets were measured in five series. During the measurement, stable environmental conditions prevailed in the building: atmospheric temperature 27-29 °C, relative humidity 31-33%, pressure at sea level 995 mbar (based on readings from the Riegl scanner).

2.3. Test base located outside the building

The second test base was set up outside the building, on its south-eastern wall, in the form of 10 sets of targets (Fig. 4). For the Riegl scanner, the same reflective targets were used as for measurements inside the building. For the Leica scanner, the diameter of the "chequerboard" was increased to 7.62 cm (≈3 inches) and the targets were laminated to increase their resistance to weather conditions.

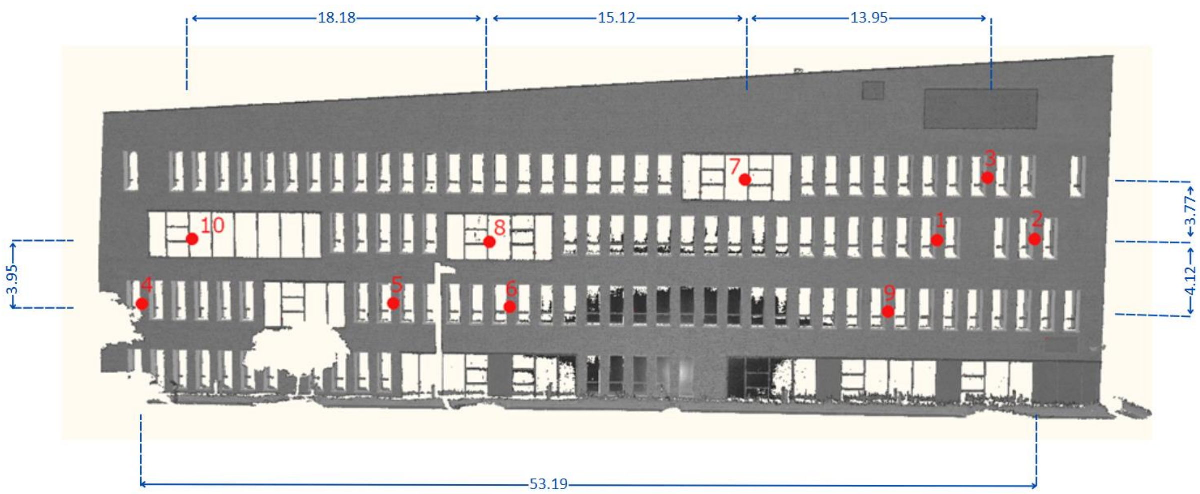

Fig. 4. Arrangement of targets on the external wall of the building (dimensions are given in meters)

For each instrument, measurements were taken from three positions (Fig. 5). Two of them (S1 and S2) were measuring pillars with a forced centring and the third position above the ground point P, which was stabilised with a metal bolt.

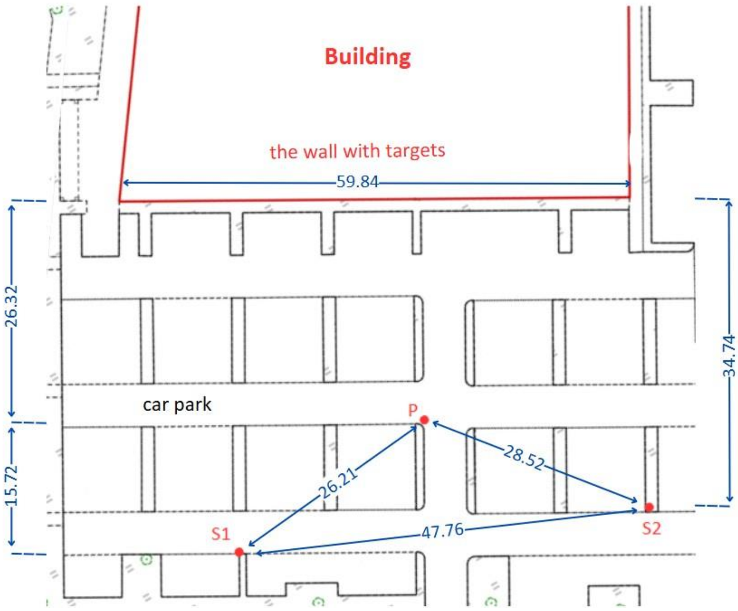

Fig. 5. Arrangement of instrument positions outside the building (dimensions are given in meters)

At the beginning, all targets were measured with a Trimble S3 total station from three positions (S1, S2, and P) using the so-called three-tripod method, in three measurement series. Then measurements were taken with the Leica scanner from the same positions, with a three-time measurement of all visible black-and-white targets at each scanner position. In the next step, analogous measurements of reflective targets were taken with the Riegl scanner. Because of the scanner's design, it was impossible to attach it directly to the S1 and S2 pillars (no typical tribrach), so it was decided to place the tripod with the scanner as close to these pillars as possible. During the measurement, stable environmental conditions prevailed outside the building: atmospheric temperature 24-25 °C, relative humidity 45-48%, pressure at sea level of 1109 mbar (based on readings from the Riegl scanner).

2.4. Procedure for processing measurement data

According to the previous assumptions, the results of the total station measurements will be treated as reference values in relation to the results obtained from both scanners. For this purpose, the results of total station measurements inside the building were precisely adjusted using the least squares method in the local coordinate system, assuming the invariance of the S1 position and assuming the known azimuth of the S1-S2 segment. This ensured the parallelism of the Y-axis of the local coordinate system with the selected building elevation. The results of the total station measurements outside the building were developed in two stages. First, only the total station positions were precisely adjusted using the least squares method (in the local coordinate system), assuming the invariance of the P position and assuming the known azimuth of the P-S2 segment. Then, the results of the measurements of the targets were precisely adjusted in relation to the previously adjusted instrument positions, treating the coordinates of the positions as error-free. The accuracy characteristics of the adjusted target coordinates, treated as reference values, are presented in Table 2.

As a result of processing the point clouds in native software dedicated to both tested scanners (Leica Cyclone and Riegl RiScan Pro), coordinates of the detected target sets were obtained for the test bases inside and outside the building. As a result, the following sets of X, Y, and Z coordinates were obtained for:

a) targets with the prefix “L” measured with the Leica scanner and measured with a total station (as reference values) for a test base inside the building
b) targets with the prefix “R” measured with the Riegl scanner and measured with a total station (as reference values) for a test base inside the building
c) targets with the prefix “L” measured with the Leica scanner and measured with a total station (as reference values) for a test base outside the building
d) targets with the prefix “R” measured with the Riegl scanner and measured with a total station (as reference values) for a test base outside the building

Table 2. Characteristics of the adjustment results

Parameter	**Least square adjustment inside the building**	**Least square adjustment outside the building**
Horizontal position error for the “worst” point	0.5 mm	0.6 mm
Mean square error of point position	0.4 mm	0.4 mm
Vertical position error for the “worst” point	0.3 mm	1.5 mm
Mean square error of point height	1.9 mm	0.9 mm

The study of the accuracy of the scanners began with an analysis of spatial distance deviations. As mentioned earlier, scanner measurements were performed in several series at each position, and the target coordinates obtained from each series were used for calculations. For each set of coordinates, spatial distances were calculated for each possible pair of detected targets. For measurements with the Riegl scanner, 91 sections were obtained inside the building and 42 sections outside the building. For measurements with the Leica scanner, 66 sections were obtained inside the building and 45 sections outside the building. The differences in the number of sections resulted from the unequal number of targets detected for individual scanners and individual scanner position. Then, for each spatial distance measured from the same position in several series, an average value and its standard deviation were calculated. If a specific spatial distance could be calculated from several scanner positions (measurements outside the building), the average value of all measurements performed outside the building (from several positions) and its standard deviation were also calculated. The mean values were compared with the reference values and a mean absolute error (*MAE*) was calculated (2.1):

$$MAE = \frac{|x_{mean} - x_{ref}|}{n}, \qquad (2.1)$$

where: x_{mean} – average value of all measurement series; x_{ref} – reference value; n – number of observations (number of segments between targets).

The second aspect analysed was deviations of spatial angles. Using the coordinates of detected targets (from each data set: Leica, Riegl and total station), nine spatial angles inside the building and five spatial angles outside the building were determined. The obtained values of spatial angles from individual measurement series were averaged for individual instrument positions and then compared with the reference values.

The third aspect analysed was deviations of the spatial coordinates of the detected targets from different instruments (Leica, Riegl, and total station). Since the point clouds were not obtained in the common coordinate system, it was decided to perform a spatial isometric transformation (6-parameter) from the local systems of each scanner to the reference coordinate system from the total station. Potential inaccuracies of the target coordinates detected by the scanners will affect the transformation results, in the form of an increased global transformation error, as well as increased residuals of the X, Y, Z coordinates of individual targets.

The fourth aspect analysed was deviations of the distance between the spheres and the accuracy of the sphere diameter approximation. The spheres were screwed to a stand (Fig. 3), so they maintained mutual position constancy. The stand was placed at specific distances from the scanner (3 m, 6 m, 9 m, 12 m, and 15 m) and scanning of the stand was performed. On the basis of the point cloud, the distances between each pair of spheres on the stand (K1-K2, K1-K3, K2-K3) were calculated, separately for each position of the stand (distance between the stand and the scanner). Then, for all measurements at a given scanner position (regardless of the scanner distance to the stand), an average distance and its standard deviation for each pair of spheres on the stand were calculated.

Additionally, a value of the approximated sphere diameter from each measurement was analysed, and then the average value and standard deviations of the sphere diameter were calculated. With the knowledge of the actual diameter of the sphere, an *MAE* was calculated. The sphere scanning procedure is automatic in the case of the Leica scanner, while the Riegl scanner is not adapted to automatic sphere detection. Therefore, two independent sphere measurements were performed for the Riegl scanner. In the first one, the scanning angular density was changed in such a way that regardless of the distance of the stand with the spheres from the scanner, a similar cloud density was maintained. In the second measurement, the spheres were scanned without changing the standard scanning angular density (20 mdeg $\approx 222^{cc}$), which resulted in the spheres placed farthest from the scanner being described by significantly fewer points.

3. RESULTS

3.1. Results of the analysis of spatial distance deviations between targets

The results of the spatial distance deviation tests for the Riegl scanner are presented in Table 3. For the measurements taken inside the building, the average standard deviation is 0.9 mm, and for more than 90% of the segments it is in the range of 0-1.5 mm (Fig. 6a), which indicates high repeatability of the results. The distribution of differences in the average spatial distance from the reference values inside the building (Fig. 6b) is close to the Gaussian distribution, which may result from the fact that the measurements were taken from a single position and there were no additional interferences in the form of systematic errors. The *MAE* of the differences is equal to 1.9 mm.

For the measurements outside the building (Table 3), the average standard deviation is 0.8 mm and it is 0.1 mm smaller than the one taken inside the building. However, the individual standard deviations reached slightly higher values (Fig. 6c), that clearly differ from the other standard deviations, which may indicate inaccurate detection of the target centre by the scanner. The results of the differences in the average distances from the reference values are worth noting, where all the differences are non-positive. This means that the distance to the point measured by the scanner is too small because, in theory, the average absolute error should be close to 0, and the distribution of the difference values should be normal. Meanwhile, the average absolute error was 5.3 mm, which is a worse result than for the measurements inside the building. In the case of the external measurements, the distribution of the average distance difference values (Fig. 6d) is much less orderly, which may have been caused by the measurement performed at three positions, that differed in the number of observations (the number of segments between the targets measured from individual scanner positions).

Similarly, a study of spatial distance deviations for the Leica scanner was carried out (Table 4). The results obtained for the measurements inside the building indicate high precision of measurements (average standard deviation at the level of 0.6 mm), and the distribution of standard deviation values (Fig. 7a) is close to the right-sided asymmetric distribution, which is desirable for this statistic, because it means that most observations have a low deviation value. The distribution of the values of differences in the average spatial distance from the reference values (Fig. 7b) does not show regularity, and the vast majority of results are positive, suggesting that the distances from the scanner measurement are greater than the reference values. For the measurements taken outside the building, the average standard deviation is 1.0 mm (Table 4), and the distribution of standard deviations (Fig. 7c) also shows a right-sided asymmetry. The MAE of these measurements was 0.9 mm, which is the best result within the research carried out, and the *MAE* distribution (Fig. 7d) is quite diverse with ranges of values of (-1.0; -1.5> and (1.0;1.5> mm being predominant.

Table 3. Analysis of the deviations of spatial distances between targets for the Riegl scanner

Riegl VZ-400i	**Standard deviations of spatial distances [mm]**			**Differences between the mean spatial distance and the reference value [mm]**			***MAE* of differences between the average spatial distances and the reference values [mm]**
	min.	max.	average	min.	max.	average	
Test base located inside the building	0.1	1.8	0.9	-5.7	4.4	-0.8	1.9
Test base located outside the building	0.0	2.8	0.8	-12.0	0.0	-5.3	5.3

Fig. 6. Analysis of deviations in spatial distances between targets for the Riegl scanner

Table 4. Analysis of the deviations of spatial distances between targets for the Leica scanner

Leica ScanStation C10	**Standard deviations of spatial distances [mm]**			**Differences between the mean spatial distance and the reference value [mm]**			***MAE* of the differences between the average spatial distances and the reference values [mm]**
	min.	max.	average	min.	max.	average	
Test base located inside the building	0.0	1.3	0.6	-0.4	3.7	1.5	1.6
Test base located outside the building	0.1	2.7	1.0	-1.7	2.1	0.2	0.9

Fig. 7. Analysis of deviations in spatial distances between targets for the Leica scanner

3.2. Results of the analysis of spatial angle deviations between targets

The spatial angle analysis for the results of the measurement inside the building with the Riegl scanner (Table 5) indicates high precision of the measurements at the level of 31^{cc}, with an *MAE* of 96^{cc}. However, there are deviations from the reference values reaching -245^{cc}. For the measurements outside the building, the average standard deviation is almost twice as large as for the measurements inside and is equal to 59^{cc} (Table 5). The *MAE* is 73^{cc}. The high value of this deviation may be caused a the smaller number of angles analysed and a limited number of observations at each site, because not all the targets creating the individual spatial angles taken for analysis were detected at each position.

Table 5. Analysis of the deviations of spatial angles between targets for the Riegl scanner

Riegl VZ-400i	**Standard deviations of spatial angles [cc]**			**Differences between the mean spatial angle and the reference value [cc]**			***MAE* of the differences between the average spatial angles and the reference values [cc]**
	min.	max.	average	min.	max.	average	
Test base located inside the building	16	49	31	-245	110	-42	96
Test base located outside the building	4	152	59	-180	52	-49	73

The results of the spatial angle deviation test for the Leica scanner are summarised in Table 6. Higher measurement precision was obtained for the measurements inside the building, but the *MAE* was lower for the measurements outside the building.

Table 6. Analysis of the deviations of spatial angles between targets for the Leica scanner

Leica ScanStation C10	**Standard deviations of spatial angles [cc]**			**Differences between the mean spatial angle and the reference value [cc]**			***MAE* of the differences between the average spatial angles and the reference values [cc]**
	min.	max.	average	min.	max.	average	
Test base located inside the building	7	32	17	-125	132	-4	54
Test base located outside the building	5	79	33	4	50	39	29

3.3. Results of the analysis of coordinate deviations between targets

The results of the isometric transformation (6-parameter) from the scanner's own coordinate system to the reference system are summarised in Table 7. It can be seen that both scanners achieved similar results for the measurements made inside the building. For the measurements made outside the building, 3D transformation errors increased for the two positions S1 and P measured with the Riegl scanner.

3.4. Results of the analysis of the diameters of the spheres and the mutual distances between the spheres

The calculated distances between the centres of the spheres (Table 8) show high repeatability for both scanners, especially for the Riegl scanner. Differences in the average values of the distances between the spheres between the two scanners reach only 0.2 mm, suggesting high accuracy of scanning of solids and correctness of the algorithm for finding the centre of a sphere. According to the manufacturer, the scanned spheres have a diameter of 154 mm. When this value is compared with the approximation results (Table 9), it can be seen that the spheres were fitted more accurately based on the point clouds from the Leica scanner (*MAE* = 1.0 mm). Paradoxically, manual setting of the scanning density to maintain a similar number of points representing the scanned sphere regardless of its distance from the scanner (first Riegl data set) did not improve the quality of the approximation of the sphere diameter (*MAE* = 2.0 mm). A slightly better result was obtained by scanning with constant angular density (*MAE* = 1.5 mm). The second data set from Riegl also has slightly worse repeatability of the results for individual ranges of stand-to-scanner distances.

Table 7. The accuracy of the coordinates transformation for the Riegl scanner (blue) and the Leica scanner (green)

Riegl & Leica		Instrument position	Mean error of: 3D transformation [mm]		translation [mm]		rotation [cc]		Axis	Number of targets tested	
Test base located:	inside the building	S1	1.3	0.9	0.4	0.3	42	22	X	14	12
					0.4	0.3	26	28	Y		
					0.4	0.3	19	14	H		
	outside the building	P	3.4	0.7	1.1	0.2	203	54	X	10	10
					1.1	0.2	175	9	Y		
					1.1	0.2	41	9	H		
		S1	3.0	0.8	1.4	0.3	376	78	X	5	6
					1.4	0.3	346	82	Y		
					1.4	0.3	58	14	H		
		S2	1.0	0.9	0.4	0.3	54	52	X	5	9
					0.4	0.3	93	53	Y		
					0.4	0.3	49	13	H		

Table 8. Comparison of distances between sphere centres for both scanners

Scanner	Data set	Distance designation	Distances between the spheres obtained from the measurement [m] for the distances tested from the scanner to the stand: 3 m	6 m	9 m	12 m	15 m	Standard deviation [mm]	Mean [m]
Leica ScanStation C10	1	K1-K2	0.4938	0.4936	0.4934	0.4935	0.4935	0.2	0.4936
		K1-K3	0.9996	0.9985	0.9984	0.9981	0.9982	0.6	0.9986
		K2-K3	0.5059	0.5050	0.5050	0.5047	0.5048	0.5	0.5051
Riegl VZ-400i	1	K1-K2	0.4938	0.4935	0.4936	0.4937	0.4937	0.1	0.4937
		K1-K3	0.9991	0.9986	0.9985	0.9987	0.9989	0.2	0.9988
		K2-K3	0.5054	0.5052	0.5050	0.5051	0.5053	0.2	0.5052
	2	K1-K2	0.4940	0.4935	0.4936	0.4936	0.4936	0.2	0.4937
		K1-K3	0.9992	0.9985	0.9987	0.9987	0.9986	0.3	0.9987
		K2-K3	0.5053	0.5051	0.5052	0.5052	0.5051	0.1	0.5052

Table 9. Comparison of the diameters of the approximated spheres at different distances from the scanner

Scanner	**Data sets**	**Sphere number**	**Approximated diameter of the sphere [mm] for the distances tested from the scanner to the stand:**					**Std. dev. [mm]**	**Mean [mm]**	***MAE* [mm]**
			3 m	**6 m**	**9 m**	**12 m**	**15 m**			
Leica C10	**I**	**K1**	156	155	154	153	156	1.3	154.8	1.0
		K2	155	154	154	153	153	0.8	153.8	
		K3	155	156	154	153	152	1.6	154.0	
	Std. dev. [mm]		0.6	1.0	0.0	0.0	2.1			
	Mean [mm]		155.3	155.0	154.0	153.0	153.7			
Riegl VZ-400i	**I**	**K1**	151	151	153	154	155	1.8	152.8	2.0
		K2	150	151	151	153	152	1.1	151.4	
		K3	151	151	152	154	155	1.8	152.6	
	Std. dev. [mm]		0.6	0.0	1.0	0.6	1.7			
	Mean [mm]		150.7	151.0	152.0	153.7	154.0			
	II	**K1**	153	152	154	154	155	1.1	153.6	1.5
		K2	151	151	152	154	152	1.2	152.0	
		K3	150	152	152	154	155	1.9	152.6	
	Std. dev. [mm]		1.5	0.6	1.2	0.0	1.7			
	Mean [mm]		151.3	151.7	152.7	154.0	154.0			

4. DISCUSSION

The results of the control of the deviations of the spatial distances between the targets placed inside the building are very similar for both tested scanners and are within the values indicated by the manufacturers. A slightly larger range of differences can be observed between the mean spatial distance and the reference value for the Riegl scanner. At the same time, this range is quite symmetric with respect to the zero value. For the Leica scanner, positive values of deviations from the reference values prevail. In the case of measurements of targets located outside the building, high repeatability of results (measurement precision) was observed for both scanners, but deviations from the reference values are much larger for the Riegl scanner. Inside the building, the targets were placed around one scanner station, while outside, the targets were glued to a flat façade and the measurement was carried out from three stations. Therefore, the location of the targets outside was quite unfavourable, and there were quite sharp angles of reflection of the laser beam from distant targets. The results obtained suggest worse accuracy of the automatic detection of the target centre for the Riegl scanner. This could be due to the greater distance between the scanner and the targets than inside the building and the preservation of the same diameter of the reflective target, while the diameter of the "chequerboard" used outside for the Leica scanner was increased from 5 cm to 7.62 cm (3 inches). An additional difficulty for both scanners was the glass surface of a large part of the façade on which the targets were glued.

In the case of spatial angles between the targets, the accuracy of their determination cannot be directly compared with the accuracy of measuring angles at the scanner station indicated given in the manufacturer's specification because these are different angles. Despite this, it can be seen that both for the measurements inside and outside the building, the accuracies obtained with the Leica scanner are slightly better than those for the Riegl scanner.

Taking into account the analysis of the accuracy of determining the coordinates of the targets using the isometric spatial transformation method, this issue is of particular importance when terrestrial laser scanning is used to study displacements and deformations of engineering objects. To determine displacements, two point clouds are needed to represent the geometry of the object in two different time periods but in the same coordinate system. Therefore, it is necessary to use targets with coordinates in a common coordinate system and to correctly georeference point clouds from both periods. The obtained 3D transformation error of a few millimetres is sufficient for most geodetic tasks related to monitoring changes in cubature objects over time. Of course, there are works that require higher accuracy of system restoring, but then it is necessary to use continuous-wave scanners, that have a smaller 3D-position error of a single scanned point and lower measurement noise.

An interesting issue is a use of spheres to register point clouds from different positions and to assign georeference. A flat reflective target stuck on a wall of a building provides good reflection of the laser beam for the scanner station located perpendicular to the wall with the target. For sharp reflection angles, the probability of automatic detection of the target and the accuracy of correct calculation of the coordinates of the centre of the target decrease significantly. Flat targets can be mounted on rotating adapters, but such method increases the workload, as the target needs to be rotated perpendicularly to each next scanner station. In addition, there is a problem of precise centring of such a rotating target and a possible correction of the eccentricity of the laser beam reflection point by introducing a correction in the form of an addition constant. An alternative solution is to use reference spheres, which allows for correct and precise detection of the sphere centre from different directions. The Leica scanner has built-in tools for automatic scanning and detection of the sphere centre. The tests carried out confirmed high accuracy of these tools. The manufacturer of the Riegl scanner does not provide for the use of reference spheres to join stations and assign georeference, so calculations related to the results of scanning of the spheres were performed in the Leica Cyclone software. The deviations of the distances between the spheres obtained from the measurements using the Riegl scanner are lesser than those obtained using the Leica scanner. However, the accuracy of the approximation of the diameters of the spheres for the Riegl scanner was worse. This indicates a lack of calibration of the parameters of the laser signal reflected from the sphere surface. For scanning flat reflective targets and geodetic prisms, the Riegl scanner has a special measurement mode, but the reflection coefficient of the spheres is “unknown” for it and, therefore, there is slightly higher measurement noise. Changing the angular density of the sphere scanning does not have a significant effect on the accuracy parameters of the approximation of the diameters of the reference spheres. For the distances of 9 m and 12 m (Table 9 - Leica data sets), as well as for the distances of 6 m and 12 m (Riegl data sets) approximated diameters were identical for all spheres, so the standard deviation values were equal to 0. It could be something characteristic of the relevant distances. For short distances (about 3 m) the reflection of the laser beam may be too strong and may produce some measurement noise. For distances above 12 m accuracy decreases. The distances between 6 m and 12 m seem to be optimal for georeferencing with spheres.

5. CONCLUSIONS

The analyses of the accuracy of two pulsed laser scanners concerned a study of deviations of spatial distances, spatial angles, and coordinates of the target centres in relation to the reference measurements of these targets made with a precise total station. Therefore, a key to the deviations obtained was correct and precise detection of dedicated targets, that were different for both scanners. In favourable measurement conditions (optimal arrangement of the targets inside the building), both scanners confirmed high measurement accuracy. The *MAE* of the differences between the average spatial distances and the reference values was 1.6 mm for the Leica scanner and 1.9 mm for the Riegl scanner. These values are acceptable for most surveying tasks requiring high accuracy, e.g. inspection of steel structure dimensions, precise inventories of industrial installations, modernization of facilities or preparation of digital twins of historic buildings. With the unfavourable arrangement of targets on the flat shiny façade of the building and with lower efficiency of detecting the target centre, the accuracy of the Riegl scanner deteriorated in relation to that of the Leica scanner. This confirms a need for careful selection of a location and size of reflective targets for a specific measurement object. The immediate surroundings around the target are also of great importance. Strongly reflective, shiny, and glass surfaces should be avoided, which may make it difficult or even impossible to correctly detect, scan, and calculate coordinates of the target centre in an automatic way.

The standard deviations of spatial angles for the Leica scanner did not exceed the value indicated by the manufacturer for the accuracy of a single angle measurement (37^{cc}). Inside the building, the standard deviation of spatial angles was 17^{cc}, and this result was even twice as good as that obtained outside (33^{cc}). In the case of the outside measurements for the Riegl scanner, the standard deviation of spatial angles was 59^{cc} and exceeded (almost twofold) the value indicated by the manufacturer for the accuracy of a single angle measurement (31^{cc}). Similarly to the control of spatial distance deviations, the less satisfactory result of the Riegl scanner for the outside measurements could have been caused by too small a size of the targets for a given scanning distance, which resulted in poorer accuracy of detection of the targets centres.

The mean error of the 3D transformation can be used to assess the scanner's suitability for measuring displacements and deformations when reproducing the georeferencing from the initial measurement is very important. For all positions tested, the Leica scanner achieved results below 1.0 mm, which fully confirms its suitability for the above applications. In the case of the Riegl scanner, this accuracy was varied: 1.3 mm inside the building (similarly to Leica) and from 1.0 mm to 3.4 mm outside the building. This less than optimal accuracy (achieved for the P station) may still be acceptable for some objects covered by displacement monitoring, such as landslides.

To answer the question posed in the Introduction, the analyses carried out prove that even older scanner models (ScanStation C10) have high measurement accuracy, useful in engineering surveying, despite a significantly slower measurement process compared to modern scanner models. It also takes some time to level the instrument and turn it off before moving it to the next position. On the other hand, a scanner equipped with a tribrach allows for precise centring of the device as well as measurement using the so-called three-tripod method. In order to reduce the measurement time, a lower point cloud resolution can be used, but this will reduce the accuracy of detail mapping for the measured objects. A practical limitation may also be the laser class, which will make measurements in the vicinity of bystanders difficult.

A use of reference spheres to connect stations is recommended in the literature and is provided by the manufacturer of the Leica scanner. As in previous tests, high accuracies were obtained for the Leica scanner: the *MAE* of a sphere approximated the diameter equal to 1.0 mm and the standard deviation of distances between spheres was less than 0.6 mm. The Riegl scanner was not designed by the manufacturer to be used with reference spheres. However, the accuracies obtained with it are similar to those obtained with the Leica scanner. For the Riegl scanner, the *MAE* of a sphere approximated the diameter equal to 1.5-2.0 mm and the standard deviation of distances between spheres was less than 0.3 mm. This confirms practicality of using reference spheres for georeferencing during engineering surveying work, also for with Riegl scanner.

The authors plan to continue their research on the empirical accuracy of laser scanners in two aspects. The first will be the influence of the angles of reflection of the targets on the effectiveness and accuracy of detecting target centres. The second will be direct comparisons of angles and spatial distances from the scanner to the targets with the results of the reference measurements.

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