Study into Point Cloud Geometric Rigidity and Accuracy of TLS-Based Identification of Geometric Bodies

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Abstract. Capability of obtaining a multimillion point cloud in a very short time has made the Terrestrial Laser Scanning (TLS) a widely used tool in many fields of science and technology. The TLS accuracy matches traditional devices used in land surveying (tacheometry, GNSS – RTK), but like any measurement it is burdened with error which affects the precise identification of objects based on their image in the form of a point cloud. The point’s coordinates are determined indirectly by means of measuring the angles and calculating the time of travel of the electromagnetic wave. Each such component has a measurement error which is translated into the final result. The XYZ coordinates of a measuring point are determined with some uncertainty and the very accuracy of determining these coordinates is reduced as the distance to the instrument increases. The paper presents the results of examination of geometrical stability of a point cloud obtained by means terrestrial laser scanner and accuracy evaluation of solids determined using the cloud. Leica P40 scanner and two different settings of measuring points were used in the tests. The first concept involved placing a few balls in the field and then scanning them from various sides at similar distances. The second part of measurement involved placing balls and scanning them a few times from one side but at varying distances from the instrument to the object. Each measurement encompassed a scan of the object with automatic determination of its position and geometry. The desk studies involved a semiautomatic fitting of solids and measurement of their geometrical elements, and comparison of parameters that determine their geometry and location in space. The differences of measures of geometrical elements of balls and translations vectors of the solids centres indicate the geometrical changes of the point cloud depending on the scanning distance and parameters. The results indicate the changes in the geometry of scanned objects depending on the point cloud quality and distance from the measuring instrument. Varying geometrical dimensions of the same element suggest also that the point cloud does not keep a stable geometry of measured objects.

1. Introduction
Terrestrial Laser Scanning (TLS) is a well-known measurement technology, commonly used for a wide range of engineering solutions. It ensures fast acquisition of spatial information on many different kinds of places and objects. All 3D data is specified with the accuracy of a few millimetres [1]. Laser scanners use one of the two types of distance measurements: either the pulse measurement, which involves measuring the time of flight of a laser beam at the distance between the instrument and object, or phase measurement, which involves determining the phase shift of a transmitted and received electromagnetic wave. While the distance is measured, the instrument's rotation angle is registered, which instrument rotates 360° horizontally. To measure the vertical angle, swivel mirrors are used, which diffuse the laser
beam in the proper direction [2]. As a result, in a very short period of time, conditions are created for the acquisition of multimillion spatial data in the form of a point cloud. Each and every element of such a cloud has specific coordinates X, Y, Z, determined with a classic polar measurement method [3].

The TLS technology is used for evaluating the geometry of solids, as well as for creating 3D models of places and objects. A point cloud may serve as the basis for spatial analyses, dimensional inspections and structural geometry examination. Such studies are aimed at: providing information about buildings - Building Information Modelling (BIM), detecting structural errors and identifying potential errors of an object's components [4].

If an inspection of objects is to be reliable, data is necessary whose measurement uncertainty must be strictly specified as well as low and reliable enough to prevent gross analytical errors [5]. In reverse engineering processes and during the automated creation and modelling of solids, a cloud of points is very often the best tool to provide a comprehensive source of object-related data. It is the cloud that contains accurate geospatial information in the form of points representing the object surface as coordinates X, Y and Z. The combination of TLS data and other types of spatial data is more and more frequently used in science and technology, since it improves the quality and quantity of information intended for studies. Such synergy ensures the stability of measurement data, which results in the increased accuracy of measurement results, improves their specificity and allows their further application [6].

Despite the high accuracy of scanning, any point cloud is affected by measurement noises and errors arising from the determination of coordinates X, Y and Z, which are specified in an indirect manner, based on results of the measurement of angles and lengths, which are also affected by this uncertainty. Coordinates are determined with the polar method, which causes the accuracy of their determination to decrease, as the distance between the instrument and measurement point increases [7]. The paper by Roca-Pardinas [8] presents the option of simulating errors related to locations of points contained in a cloud of points obtained with the TLS technology. These errors stem from the distance from the scanned object and the angle of the laser beam reflection on a particular fragment of the object. The scanner position also impacts types of errors in the determination of coordinates made while scanning. Greatest errors occurred when the measurement instrument was at a long distance from the examined object. An important issue is therefore to specify the uncertainty of cloud point locations – if a registered point cloud has a low accuracy and resolution, then high quality of studies cannot be achieved [9].

The quality of a point cloud obtained by scanning is affected by many factors, such as: correctness of work, skill in using the instrument, environmental conditions, and even the type and character of the measured object. The accuracy is further affected by the level of measurement noise; whose direct influence is difficult to define. It hinders the unambiguous identification of objects on a point cloud. Improper scanning geometry is yet another cause of measurement errors (scanning geometry interpreted as the evaluation of the impact of the incidence angle and scanner's distance in relation to the surface on the quality of the acquired cloud of points). The yielded quality of the laser signal decreases as the incidence angle and distance from the object increase, which causes the level of measurement noise to rise. All the factors mentioned above determine the accuracy with which scanned objects are identified [10].

The aim of this paper is to evaluate the geometric consistency of a point cloud used for the precise acquisition of information about objects. The studies included the rigidity and stability of the cloud as regards its various fragments, depending on the distance from the scanned object, as well as on the proper positioning: scanner – measured object.

2. Point cloud geometry – methodology of studies
For the purpose of these studies, we used the Leica P40 laser scanner and metal measurement balls, in other words solids with specific geometric dimensions, which were applied for evaluating the geometric consistency of the cloud as regards its respective fragments.
The technical specifications [11] of the Leica P40 laser scanner employed for these studies mention the accuracy of a single measurement:

- scope (distance measurement) accuracy on the order of: 1.2 mm + 10 ppm within the entire scope;
- angle measurement accuracy: horizontal angles – 8”, vertical angles – 8”.

As a result, the accuracy of 3D positions of single points is on the order of 3 mm at 50 m and 6 mm at 100 m.

The first part of the performed works entailed scanning one object from different sides. According to theoretical assumptions, the image created while scanning the object (ball) at many stations should present a uniform surface of the examined object. The respective fragments of the sphere visible on each cloud are basis for the automatic projection and reconstruction of the object, and for the determination of its centre. The centres of all the spheres of the same ball, visible from many sides, correspond to one real point – the centre of the solid. During the second part of the studies, in order to eliminate errors related to point cloud orientation, which affect the position of the geometric centre of the ball, established at various stations, only one measurement station was used, from which the ball situated at an increasing distance from the instrument was measured. The accuracy analysis included the respective study objects scanned at variable distances.

Manufacturers very often provide technical specifications of their measurement instruments, which contain information on the measurement accuracy of specific devices, determined only under laboratory conditions. In practice, it usually turns out that this accuracy is specified on an entirely different level than the accuracy under field conditions, [1]. Additionally, not all parameters of a point cloud are sufficiently controlled to ensure a proper and reliable accuracy analysis for all its elements.

The entirety of research works were carried out by their authors under field conditions to check actual conditions of scanning and generating a cloud of points with Terrestrial Laser Scanning. The works focused on evaluating the possibility and accuracy of object identification in various fragments of the cloud, including its extreme parts, where the error rate for the determination of coordinates is the highest.

2.1 Measurement with a variable distance from the object

For the field measurement, a metal ball \((d = 0.152 \text{ [m]})\) was used, attached to a stand, which ball was positioned in relation to the scanner at the distance of: 20, 40, 60, 80, 100 and 120 [m] (Figure 1). The TLS measurement was conducted for every ball location in two resolutions: 2 [mm] / 20 [m] and another, possibly the highest resolution the scanner was capable of operating with as for the set distance. All the measurements were carried out at one scanner station so that all of them had a local system of coordinates.

![Figure 1. Measurement ball stations in relation to the scanner](image)
The indoor works were performed with the Leica Cyclone software. Having imported the measured point clouds, points were selected to represent the ball spheres for an appropriate scanning distance and resolution. The following tasks were completed for the obtained sets of points:

- automatic matching a ball to a sphere marked by points
- automatic matching a ball with reference dimensions \(d = 0.152 \text{[m]}\) to point clouds representing a specific ball location

Both the matched ball and the one with the set diameter were generated on the basis of the same cloud points with the least squares method. As for the matched balls, information was acquired on their diameters and accuracy with which they were matched, as well as coordinate values for the ball centre; Table 1 and 2 contain the results.

**Table 1. Measurement of the diameters and coordinates of the centre of the balls generated on the basis of the point clouds acquired at various distances and at a constant scanning resolution**

| Distance [m] | Scanning resolution | ball diameter | accuracy | x     | y     | z     | Reference [m] | X     | Y     | Z     |
|-------------|---------------------|---------------|----------|-------|-------|-------|---------------|-------|-------|-------|
| 20          | 2 mm / 20 m         | 0.152         | 0.001    | 18.983| -6.679| -1.716| 0.152         | 18.983| -6.679| -1.717|
| 40          | 2 mm / 20 m         | 0.153         | 0.002    | 37.998| -13.799| -1.671| 0.152         | 37.995| -13.796| -1.676|
| 60          | 2 mm / 20 m         | 0.159         | 0.002    | 56.858| -20.900| -1.538| 0.152         | 56.852| -20.901| -1.541|
| 80          | 2 mm / 20 m         | 0.154         | 0.003    | 75.726| -28.451| -1.176| 0.152         | 75.725| -28.452| -1.175|
| 100         | 2 mm / 20 m         | 0.164         | 0.002    | 94.454| -35.789| -0.500| 0.152         | 94.445| -35.789| -0.503|
| 120         | 2 mm / 20 m         | 0.168         | 0.003    | 113.548| -43.171| 0.098 | 0.152         | 113.539| -43.170| 0.098 |

**Table 2. Measurement of the diameters and coordinates of the centre of the balls generated on the basis of the point clouds acquired at various distances and at the highest possible scanning resolution**

| Distance [m] | Scanning resolution | ball diameter | accuracy | x     | y     | z     | Reference [m] | X     | Y     | Z     |
|-------------|---------------------|---------------|----------|-------|-------|-------|---------------|-------|-------|-------|
| 20          | 2 mm / 20 m         | 0.152         | 0.001    | 18.983| -6.679| -1.716| 0.152         | 18.983| -6.679| -1.717|
| 40          | 2 mm / 40 m         | 0.151         | 0.002    | 37.996| -13.797| -1.672| 0.152         | 37.995| -13.797| -1.676|
| 60          | 2 mm / 60 m         | 0.153         | 0.002    | 56.855| -20.900| -1.537| 0.152         | 56.851| -20.901| -1.541|
| 80          | 3 mm / 80 m         | 0.154         | 0.003    | 75.726| -28.451| -1.176| 0.152         | 75.725| -28.453| -1.174|
| 100         | 4 mm / 100 m        | 0.159         | 0.003    | 94.450| -35.790| -0.500| 0.152         | 94.445| -35.790| -0.503|
| 120         | 5 mm / 120 m        | 0.165         | 0.003    | 113.545| -43.171| 0.097 | 0.152         | 113.539| -43.168| 0.096 |

The analysis of data results boiled down to the summary and comparison of the results obtained on the basis of a point cloud and thus generated balls, which represented a geometric object with familiar parameters. The comparison included results for the diameters of the respective ball stations in relation to the distance from the scanner and in relation to the scanning resolution used for acquiring information on the surface. The results are shown in (Figure 2.).
Figure 2. Summary of results for the ball diameters depending on the scanning distance and resolution

Another part of the analysis of measurement results was the summary of results for the coordinates of the geometric ball centres at the respective stations. While generating the geometric solids based on fragments of the clouds, the least squares method was applied: to match a ball with the most suitable diameter to a sphere determined by a cloud and ball with the set diameter compliant with the real dimension. As a result, four sets of ball coordinates X, Y and Z were obtained at each measurement station:
1. ball matched to a point cloud generated by scanning with a constant resolution;
2. ball with the set diameter matched to a point cloud generated by scanning with a constant resolution;
3. ball matched to a point cloud generated by scanning with the highest possible scanning resolution;
4. ball with the set diameter matched to a point cloud generated by scanning with the highest possible scanning resolution;

As a reference value, we used the coordinates obtained for the measurements performed according to Pt. 4, which value reflected the real geometric dimensions of the ball and was acquired with the highest possible accuracy and qualitative parameters.

The summary of these results is presented in Table 3. The table contains the comparison of coordinates X, Y and Z presented in Table 1 and 2, and distance \( m_p \) between the points representing the geometric ball centres, which distance was determined on the basis of the following equation:

\[
m_p = \sqrt{(X_n - X_r)^2 + (Y_n - Y_r)^2 + (Z_n - Z_r)^2}
\]

Where:
Xn, Yn, Zn – coordinates of the centre of the compared ball \( n \) (\( n=1, 2, 3 \))
Xr, Yr, Zr – coordinates of the centre of the reference ball

Table 3. Comparison of the values of coordinates X, Y and Z – centres of the respective balls (sets 1-3) – with coordinates of the reference ball centre (set 4) and distances between the centres:

|   | \( \Delta X \) | \( \Delta Y \) | \( \Delta Z \) | \( m_p \) |
|---|---|---|---|---|
| a) | 0.000 | 0.000 | 0.001 | 0.001 |
|   | 0.003 | -0.002 | 0.005 | 0.006 |
|   | 0.007 | 0.001 | 0.003 | 0.008 |
|   | 0.001 | 0.002 | -0.002 | 0.003 |
|   | 0.009 | 0.001 | 0.003 | 0.010 |
|   | 0.009 | -0.003 | 0.002 | 0.010 |

|   | \( \Delta X \) | \( \Delta Y \) | \( \Delta Z \) | \( m_p \) |
|---|---|---|---|---|
| b) | 0.000 | 0.000 | 0.000 | 0.001 |
|   | 0.000 | 0.001 | 0.000 | 0.001 |
|   | 0.001 | 0.001 | -0.001 | 0.001 |
|   | 0.000 | 0.001 | 0.000 | 0.001 |
|   | 0.000 | -0.002 | 0.002 | 0.003 |

|   | \( \Delta X \) | \( \Delta Y \) | \( \Delta Z \) | \( m_p \) |
|---|---|---|---|---|
| c) | 0.000 | 0.000 | 0.001 | 0.001 |
|   | 0.001 | 0.000 | 0.004 | 0.004 |
|   | 0.001 | 0.002 | -0.002 | 0.003 |
|   | 0.005 | 0.000 | 0.003 | 0.006 |
|   | 0.006 | -0.003 | 0.001 | 0.007 |
2.2 Measurement around the object

The second part of the field measurements involved using a ball with familiar geometry and laser scanner at three stations (Figure 3). The scanner stations were located at the distance of 30-40 [m] from the object, whereas the scanning process itself took place with the resolution of 2 [mm] / 50 [m]. The fixed ball was scanned from three different sides.

For processing the point clouds, we used the Leica Cyclone software, whereas for the process of orientation and combining the respective point clouds – independent station-orienting elements. The process of combining the clouds into one single object was performed with the accuracy of 4 [mm].

As a result, we obtained a summary of the three spheres, which should form a coherent whole, while their central points should be represented by one point. The juxtaposed fragments of the point clouds representing the object surfaces are shown in Figure 4.

The analysis comprised the obtained diameters of the balls generated on the basis of the respective point clouds representing a different part of the examined ball's sphere, as well as the coordinates of their centre. As for the data related to these spheres, the ball was matched with the given set parameters; similarly in this case, we carried out an analysis with coordinates X, Y and Z of their centre (Table 4).

| Station | Diameter of generated ball [m] | x   | y   | z   | Diameter of reference ball [m] | x   | y   | z   |
|---------|-------------------------------|-----|-----|-----|-------------------------------|-----|-----|-----|
| 1       | 0.150                         | -11.287 | -46.956 | -2.704 | 0.152                         | -11.285 | -46.956 | -2.705 |
| 2       | 0.159                         | -11.287 | -46.955 | -2.704 | 0.152                         | -11.286 | -46.951 | -2.704 |
| 3       | 0.161                         | -11.287 | -46.956 | -2.705 | 0.152                         | -11.282 | -46.958 | -2.705 |
Subsequently, with all the three spheres representing the measured object surface, by applying the least squares method, the reference ball was created with the diameter of 0.156 [m] and centre coordinates of \( X = -11.283 \), \( Y = -46.955 \) and \( Z = -2.705 \).

Among the respective balls, generated on the basis of the respective spheres, and the reference ball, differences in the values of coordinates \( X \), \( Y \) and \( Z \) were determined, together with the vector of their centre's shift \( \mathbf{m}_p \), calculated with equation (1). The summary results are presented in Table 5a,b.

**Table 5.** Comparison of the values of coordinates \( X \), \( Y \) and \( Z \) – ball centres – at the respective stations (Table 4) with the reference ball centre coordinates and distances only between the centres: a) for the balls matched on the basis of the point cloud b) for the balls matched to the cloud with the set diameter

|       | \( \Delta X \) | \( \Delta Y \) | \( \Delta Z \) | \( m_p \) |
|-------|---------------|---------------|---------------|----------|
| a)    | -0.004        | -0.001        | 0.001         | 0.004    |
| b)    | -0.004        | 0.000         | 0.001         | 0.004    |
|       | -0.004        | -0.001        | 0.000         | 0.004    |

3. Results and discussions

The result analysis indicated the correlation between the scanning distance, resolution and accuracy of results obtained on the basis of the point cloud. The first part of the completed works involved scanning the same object at a variable distance and variable density of scanning. The works results showed the drop in the identification accuracy of the solids, as the distance from the measuring instrument increased, which also confirmed results of works by the other authors [7,8]. The values of accuracy, ball matching to the sphere fragments, contained in Table 1 and 2, as well as the summary of the diameters of the respective geometric objects (Figure 2) indicate the decrease of identification accuracy for the solids, which is the most likely attributable to the increase of measurement noises, observable especially at the edges of the point cloud. The low scanning resolution and increasing measurement uncertainty for the location of respective points in a cloud prevent the achievement of high quality of measurement results [9]. An important issue is also the precision while registering points which represent the solid surface. Figure 5 shows an image of a point cloud for a ball at 100 [m] from the scanner. In the figure you can see a precisely represented ball surface, despite a significant drop in the accuracy of the determination of coordinates of spatial points at this distance.

![Figure 5](image1.png)

**Figure 5.** View of a fragment of the point cloud representing the balls – examined object at 100 m from the scanner: a) Scanning resolution: 10 mm / 100 m – number of points representing the object: 314, b) Scanning resolution: 4 mm / 100 m – number of points representing the object: 714.
The summary and comparison of the centre coordinates for the balls generated automatically in comparison with the reference values also confirm the thesis that the identification accuracy of solids decreases as the distance increases. Special attention should be paid to shift values $m_p$ for the ball centres (Table 3). A much higher compliance is indicated by the results obtained by matching the balls with the set geometric parameters. Irrespective of the low scanning resolution, the accuracy level for ball matching is very high. The balls matched to a sphere without specifying geometric dimensions showed the decreased accuracy of matching and failure to maintain the geometric consistency of the point cloud acquired with the TLS technology. Both the diagram in Figure 2 and calculation results in Table 3 show a significant accuracy drop and decreased point cloud stability at 100 [m] in relation to the measuring instrument.

The characteristics presented by the manufacturer of the measuring device [11] specify the level of accuracy for determining coordinates of 3D points at 6 mm at the distance of 100 m. These values also confirm the field test results, where the location accuracy of the ball centres – measured objects – is determined within this value, irrespective of the scanning resolution.

Take note that changing the location of the geometric centre of the ball used as the reference object for orienting the point clouds acquired at many stations will have a significant impact on results of this orientation. The conducted tests conclusively show that during the measurements special attention should be paid to the geometry of the binding points between the respective stations, including the maintenance of similar distances of the reference balls from the respective scanning stations, as well as the density and quality of the point cloud being obtained for the reference objects.

The second part of the tests involved the juxtaposition of various fragments of the cloud of points representing a specific geometric object scanned at many stations. The analysis results for the accuracy of the centres of the balls generated on the basis of the object spheres and ball created with all the cloud points from many stations is within the error limits specified by the scanner's manufacturer. While keeping the high scanning resolution and complementarity of the points representing the whole examined object, it is possible to precisely reconstruct it using the method for identifying solids.

4. Conclusions
Regardless of it being used more widely, the TLS technology is not controlled in terms of the maintenance of geometric rigidity for respective fragments of point clouds. The identification accuracy for geometric solids is directly related to the level of accuracy and precision for the location of respective points in a cloud.

The results of the tests and analyses of the performed field works indicate the decrease in the identification accuracy for solids, as the distance increases and the scanning resolution decreases. Although the accuracy drops, the TLS measurement precision is constantly maintained on a high level. The geometric consistency of a point cloud is not kept in all its fragments due to the drop in the accuracy of the determination of coordinates $X$, $Y$ and $Z$ of a measured object, which stems from the use of the polar method for establishing values of these coordinates [7]. The least geometrically accurate and stable areas are points at edges of such clouds, especially at a distance above 100 [m] in relation to the scanner.

Furthermore, the tests showed the increased level of accuracy for the identification of geometric objects when an object was matched through specifying its real geometric parameters. Despite much measurement noise and decreased geometric stability of a cloud, especially at long distances, thanks to the maintenance of high precision for acquiring coordinates of points representing the object surface, it is possible (if additional geometric parameters of the object are provided) to accurately match it and project its actual location.
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