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Preliminary Results of Georeferencing Accuracy Using Sphere Targets in Point Cloud Registration

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Abstract. This research examines the viability of georeferencing point clouds obtained from terrestrial laser scanning (TLS) with spherical targets. Ground-based laser scanning is a modern technology for collecting spatial data about a territory. It is particularly useful for documenting immovable cultural heritage sites, restoring construction documentation for old buildings and sites with complex geometry, 3D cadastral surveys, and creating digital twins and surrogates. To achieve these goals, precise equipment is required (ground-based laser scanners) is required to achieve these goals. The resulting point cloud is usually in the local coordinate system of the instrument. However, positioning the point cloud or the model obtained from it in space requires the application of methods for transformation into a global coordinate system, known as georeferencing. This is usually achieved by using special measurement marks, which are first measured with the scanner and then coordinated by measurements with a total station. This study provides a preliminary analysis of the use of spherical marks centered on points that are coordinated by measurements with a global navigation satellite system (GNSS) in net Real Time Kinematic (RTK) mode. Currently, this mode is the most widely used for measuring points from a working geodetic base when performing cadastral activities, due to the low cost of the service and the quick final result with an accuracy of 2 cm in plan and 5 cm in elevation. This error, combined with the high accuracy (< 1 mm) of spherical mark recognition by the laser scanning data processing software, creates challenges for the successful registration and georeferencing of data. Deviations from the vertical caused by the error of GNSS measurements in height positions are analysed, and recommendations are given to overcome this problem. Results from several real cultural heritage sites surveyed using this method are presented. Conclusions and recommendations about the precision of georeferencing point clouds are presented.

Keywords: Sphere targets; georeferencing; point clouds; accuracy; registration.

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INTRODUCTION

Terrestrial laser scanning is an effective technology for providing high-precision point clouds for a variety of applications. Point clouds must be converted into a precisely defined reference frame, such as the Global Geodetic Reference System 1980 or Bulgarian Geodetic System 2005. In this paper, a method for georeferencing point clouds that provides coordinates in a geocentric frame is analysed. The transformation to the geodetic coordinate system is based on an evaluation of seven Helmert parameters using several reference points measured with GNSS (Global Navigation Satellite System).

Spherical signals are preferred in TLS due to their visibility from all angles and easy recognition in point clouds. In order to be used for georeferencing, an accurate determination of the centre of the sphere in the global coordinate system is required. This is usually achieved by measuring the position of the base on which the sphere is placed, using

a GNSS receiver, and then calculating the vertical offset to the centre of the sphere. This approach is described in a study that considers the use of spherical targets for georeferencing using GNSS RTK measurements.

The accuracy of georeferencing is usually determined by the differences between the coordinates of known points and their corresponding coordinates in the georeferenced point cloud. The points used to determine the final accuracy should not be used in determining the transformation parameters [8, 10]. Most studies on the subject [1, 2, 6] deal with one of the two issues:

- georeferencing accuracy enhancement or
- reducing the amount of work involved in georeferencing.

In addition to flat marks, spherical marks are used in the registration of point clouds obtained from terrestrial laser scanning (TLS). The alignment of flat marks can be difficult in some cases due to their limited visibility or the unfavourable angle of incidence of the laser beam. In some situations, in places with limited visibility or monotonous landscape, but also to speed up the work when scanning structures with complex geometry, it is convenient to use spherical marks. Few manufacturers sell calibrated spheres designed for laser scanning, such as Koppa, Faro and Trimble. An extensive survey has been done by [3]. Spheres vary in material, diameter and type: solid, modular (can be torn into pieces), with integrated prism, etc. Manufacturers guarantee calibration accuracy below 1 mm, tested with a coordinate measuring machine (Figure 1).

Technical specifications

Diameter	Ø 145mm (5.7")
Weight	250g
Sphericity	0.3mm at 20°C
Radius accuracy	±0.15mm at 20°C

FIGURE 1. Laser scanning sphere and technical characteristics, *https://www.geo-zona.com/produkt/nestle-sphere/*

An obstacle to their use is the cost of the original sets (for example, one sphere can cost even 200-300 euros). However, there are not many areas on the market that also have a centering device for the needs of georeferencing (Figure 2).

230mm Single Sphere

- 230 mm OD lightweight aluminum sphere
- Accuracy < 2 mm
- Painted non-glare white
- Female 5/8 x 11 threaded mounting
- Center height is 114 mm from bottom flat
- Weight 2.7 lb (1.22 kg)

P/N: 6704-001-TR

Цена: 195 euro без ДДС

FIGURE 2. Laser scanning sphere with rod mounting capability offered by Trimble

For this reason, in practice, various substitutes for spherical elements with good geometry and correct identification of the centre are often used [5] (Figure 3).

FIGURE 3. Laser scanning spheres with various accessories composed of: 6 Spheres, diameter 150 mm non calibrated (spherical deviation less than 2mm) made from plastic 6 Tripods, max. height 18 cm, made from aluminium, carry bag, *https://www.scan-go.eu/en/categoria-prodotto/products/page/3/*

POINT CLOUD REGISTRATION

The registration methods presented schematically in (Figure 4) can be divided into 2 types depending on the type of marks used:

1) Methods using discrete points - flat and volumetric marks (Figure 5) and natural points
2) Methods using surfaces.

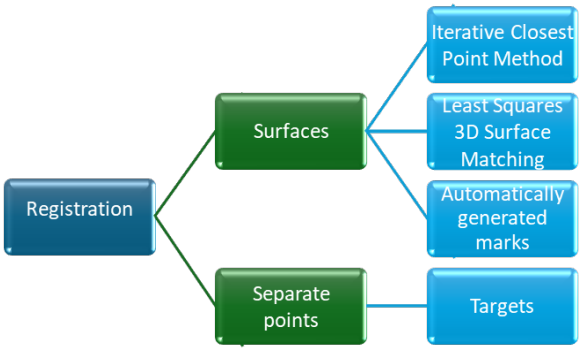

FIGURE 4. Methods for coordinate registration of point clouds

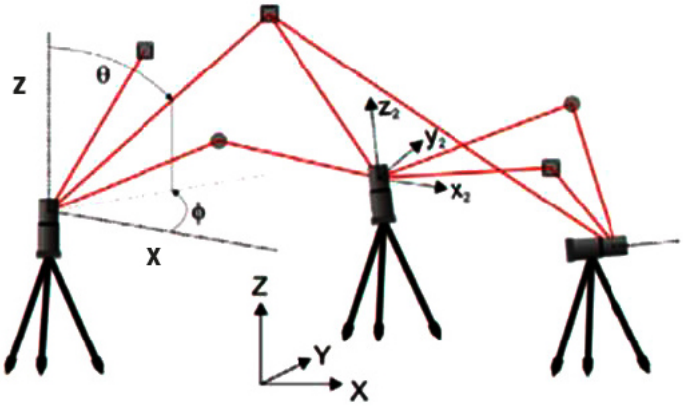

FIGURE 5. Target based registration

Classical surveying methods use small marks to minimize pointing error. In laser scanning it is desirable to use much larger structured marks or 3D shapes (e.g. spheres or cylinders) shown in Figure 6.

3D marks provided by laser scanner manufacturers, e.g., Leica and Riegl, are used to co-register point clouds. The coordinates of the marks are measured with conventional surveying instruments, then scanned and a 3D transformation is applied.

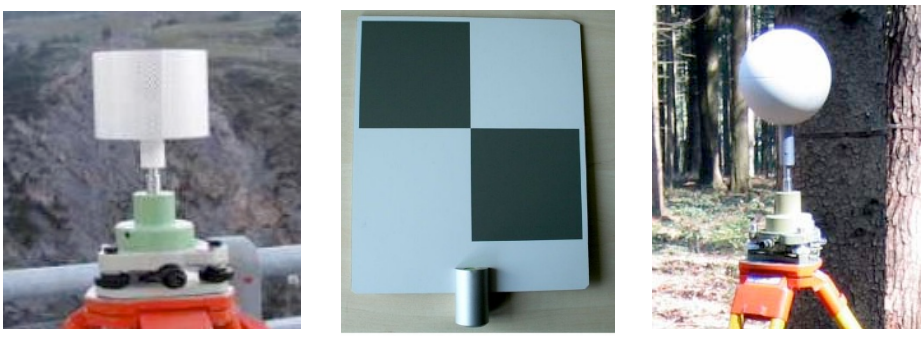

FIGURE 6. Types of marks used for registration: Cylinders (left), Plane shapes (middle), Spheres (right)

A minimum of 2 marks captured by the stations shall be used. The points should not lie on a straight line but should be evenly spaced around the instrument, if possible [1]. In practice, it has been necessary to use at least three marks with known coordinates to be able to assess accuracy. These should have been placed in the overlapping area of the point clouds.

The types of marks are:

- **Flat** - these are the most common due to their low cost. The problem with them is that it is difficult to determine their centre, in cases where the angle at which the laser falls on them is greater than 50 g and at long distances from the scanner;
- **Volumetric** - their centre can easily be determined from any scan angle.

The spherical shape is preferred because the radius of the spheres is known and the coordinates of the sphere center can be calculated by an approximation and equalization algorithm by the Least Square Adjustment [5]. These coordinates can then be entered into a classical transformation calculation using identical points. But such an approach has major drawbacks. First of all, it is necessary to use artificial marks and a great effort may be put into their placement. Secondly, only a very small fraction of the information contained in overlapping scans is used for the calculation.

Registration methods based on measurements to marks may not exploit the full potential for data accuracy. Geodetic measurements to marks naturally introduce some error that may exceed the internal scanner error [7, 8]. In addition, the marks must be kept stable throughout the data collection campaign. This can be inconvenient when scanning drags on for more than a day. On the other hand, one important advantage of mark-based methods should not be overlooked. Marks are essentially needed in projects where absolute orientation in a global coordinate system is required.

GEOREFERENCING

Point clouds received from a station are part of a local coordinate system. This coordinate system is defined by:

Home - the centre of the horizontal circle of the scanner;
Z axis – vertical axis of the scanner;
X-axis - through the zero of the horizontal circle;
Y-axis – perpendicular to the previous two axes, complements the system to the right.

The scanner measures distance, vertical angle and horizontal direction. Most laser scanner software packages provide rectangular XYZ coordinates as output, which are treated as observations (measurements). This representation further facilitates transformational formulas for georeferencing the scanned point cloud.

The unambiguous determination of the transformation parameters XsYsZs and the three rotation angles (ω, φ, χ) requires combining 6 coordinate measurements to a minimum of 2 points due to the equal scale. Typically, 3 or more control points are known and least squares adjustment method (LSAM) is performed.

The georeferencing problem in TLS involves transforming the observations from the scanner coordinate system (CS) into a spatial coordinate system (Figure 7). The spatial coordinate system can be local or global, implemented by a grid of 3D control points.

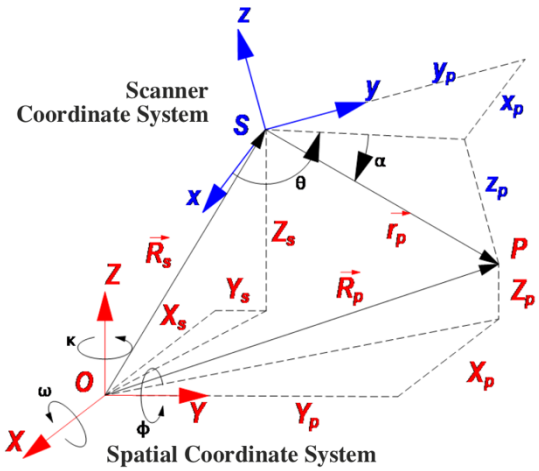

FIGURE 7. Transformation of the measurements from the scanner coordinate system into a spatial coordinate system

The transformation of the measurement vector from the scanner space to the object space is given by:

$$\overrightarrow{R_p} = M\overrightarrow{r_p} + \overrightarrow{R_s}, \tag{1}$$

where

$$\overrightarrow{r_p} = [x_p y_p z_p]^T \tag{2}$$

is the position vector of point P in the scanner CC,

$$\overrightarrow{R_p} = [X_p Y_p Z_p]^T \tag{3}$$

is the position vector of point P in the object's CS,

$$\overrightarrow{R_s} = [X_s Y_s Z_s]^T \tag{4}$$

is a vector of the position of the origin of the scanner CS in the object CS,

$$M = \begin{bmatrix} cos\varphi cos\chi & cos\omega sin\chi + sin\omega sin\varphi cos\chi & sin\omega sin\chi - cos\omega sin\varphi cos\chi \\ -cos\varphi sin\chi & cos\omega cos\chi - sin\omega sin\varphi sin\chi & sin\omega cos\chi + cos\omega sin\varphi sin\chi \\ sin\varphi & -sin\omega cos\varphi & cos\omega cos\varphi \end{bmatrix} \tag{5}$$

is the rotation matrix of the 3 angles (ω, φ and χ) about the XYZ axes.

Indirect georeferencing

In most cases, the scanner is placed at any point as a free station. This is necessary because most scanner models do not have a centring device. Measurement to points with pre-known coordinates in the coordinate system is used, which aims to convert the rest of the point cloud. An affine transformation is performed with a minimum of 3 points given by their spatial coordinates (X, Y, Z). In practice, more than 3 points are used and then an alignment according to the Least Square Adjustment Method (LSAM) is used. The points should be evenly distributed. They are called checkpoints. Their coordinates can be determined from total station or GNSS measurements.

There are methods for direct georeferencing of point clouds that use a minimum number of GNSS measurements. One such method [4] uses only two GNSS points and vertical deviation information from a global gravitational model,

such as EGM2008, to transform the point cloud into a geocentric coordinate system. This approach is particularly useful in urban environments where the availability of GNSS signals may be limited.

EXPERIMENTAL PART

Laser scanning

The scanning was performed by a Trimble TX6 scanner. The locations of the reference spheres for laser scanning are also determined – three of them with a diameter of 0.23 m are used, and they are placed on rods with clips on stabilized points (Figure 8).

FIGURE 8. Centring a reference sphere

The coordinates of the points on which the reference spheres are chosen are determined by classical angular-linear measurements with total station and geometric levelling. They are displayed in a local coordinate system.

The processing of point clouds was carried out in the Trimble RealWorks software product. The main stages that are passed through during the processing of scans are:

- Registration of point clouds with automatic generated planes;
- Point cloud georeferencing - indirect georeferencing.

Point clouds from all seven stations have been inserted. Go to the registration settings. It was chosen to be done with surfaces – recognition of identical planes.

After registration, a problem was found in one of the stations - station 6. She has not registered. The reason for this is that the scans are partial (sectoral) and when registering the clouds, station 6 did not find enough identical planes. In order to eliminate the problem, the process was repeated, and the registration was made by recognizing marks – in this case, spheres with a diameter of 0.23 m (Figure 9). The centres of the spheres are determined with an accuracy of 0.74 mm.

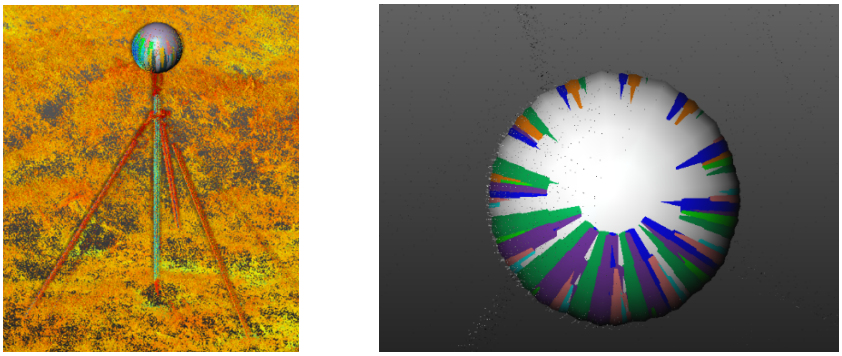

FIGURE 9. Calculated spheres from different stations

The accuracy of the detection of clouds by planes is 3.44 mm. The bigger values in errors are observed in areas with smaller percentage of overlap of the scans. Target based registration shows 2.72 mm mean distance. Results are shown in Figure 10.

Overall Cloud-to-Cloud Error: 3.44 mm

Station 001 - 6 **Station(s) with Points in Common -**

Object Name	Cloud-to-Cloud Error	Coincident Points (%)	Confidence (%)
Station 002	2.20 mm	62%	100%
Station 003	2.05 mm	63%	100%
Station 004	2.45 mm	31%	95%
Station 009	6.67 mm	31%	95%
Station 010	4.07 mm	36%	97%
Station 013	6.66 mm	18%	79%

18 STATION(S) - **Mean Distance:** 3.22 mm **Max Distance:** 5.18 mm
6 TARGET(S) - **Mean Distance:** 2.72 mm **Max Distance:** 3.71 mm

Station 001 - 4 **Scanned Objects - Mean Distance:** 1.78 mm

Object Name	Corresponding Target	Scan Per Target	Residual Error	Delta X	Delta Y	Delta Z	Fitting Error	Distance to Scanner
Station 001	--	--	--	--	--	--	--	0.00 m
002	008	11	1.23 mm	-0.53 mm	-0.44 mm	-1.02 mm	0.83 mm	6.22 m
003	009	13	2.19 mm	1.59 mm	-0.64 mm	-1.35 mm	1.08 mm	18.04 m
001	007	14	1.91 mm	0.91 mm	1.28 mm	-1.10 mm	0.96 mm	13.67 m

FIGURE 10. Plane and Target Based Registration Data Results

The indirect method of georeferencing has been applied to the project. In the Trimble RealWorks environment, the file with the measured coordinates of the spheres has been added. Identical points are set. Georeferencing was performed with an error of 12.74 mm (Figure 11). The scheme of the points is shown in Figure 12.

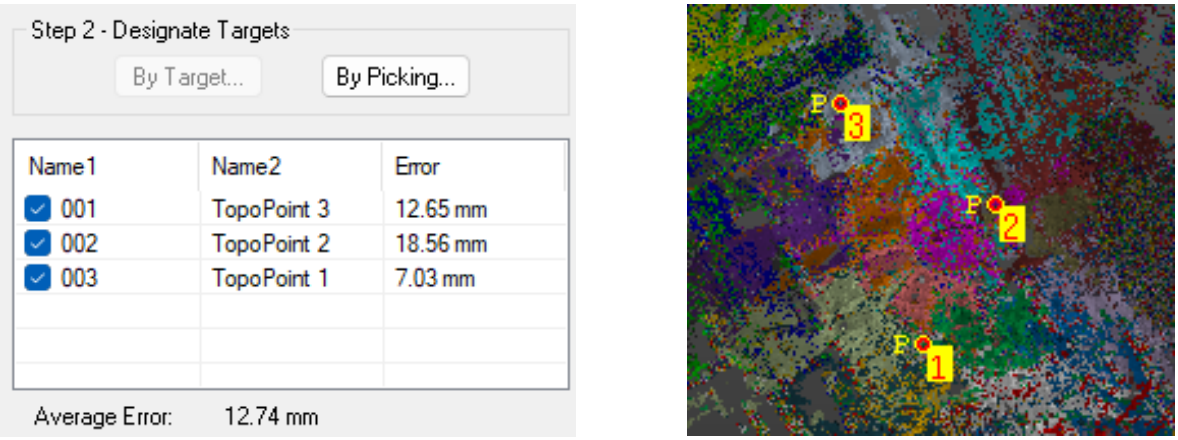

FIGURE 11. Point cloud georeferencing result

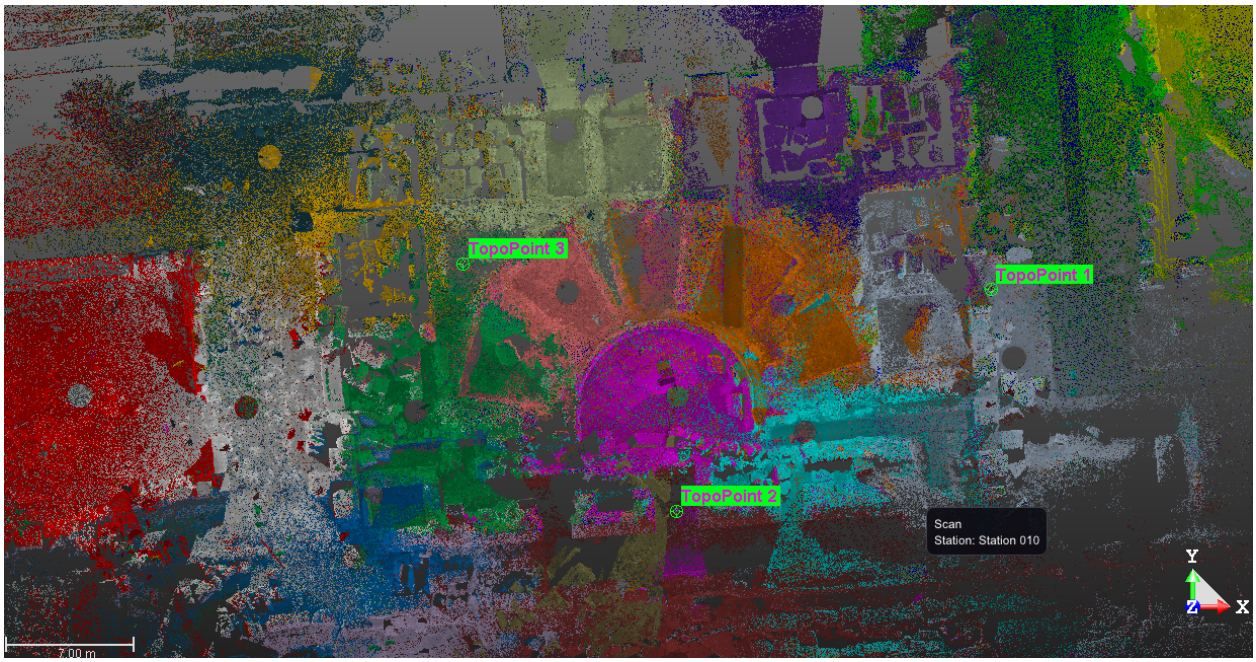

FIGURE 12. Layout of the spheres

Example with GNSS measurements

Scanning of the "Nicopolis ad Istrum" - an ancient Roman city in present-day Central Northern Bulgaria. For georeferencing of the objects, three points are selected and stabilized. They were measured with GNSS in NetRTK mode. The coordinates of the reference points are displayed in the BGS 2005 coordinate system.

Typical for this type of measurements is the resulting larger error in the heights of the points, in the order of 5 cm [2].

The following processing algorithm is applied:

1. Registration on the plain.
2. Extraction of spheres and registration.
3. Calculation of exceedances between the centres of spheres.
4. Correction of the altitudes of the GNSS measured points with the height to the centre of the sphere. Monitor whether the difference in the elevations of the spheres coincides with the measured differences in height from the scan, so as not to change the horizon (Table 1).
5. Entering the measured X and Y and the calculated H of the spheres.
6. Geo-referencing of the cloud by 3 points.

TABLE 1. Correction of the altitudes of the GNSS measured points according to the height to the centres of the spheres (**all values are in meters**)

	Topo Point	**X**	**Y**	**Z**	**dZ**	**H, m**	**dH**
target 7	3	-2,44	-13,41	1,01		116,493	
target 8	2	5,79	2,27	-0,04	1,05	115,448	1,05
target 9	1	-11,67	13,74	0,65	0,36	116,133	0,36

CONCLUSION

TLS results are an array of points with known spatial coordinates in the scanner's coordinate system, which are subsequently transformed into a desired global system. The total mean square error in determining the 3D coordinates of the points in the digital model can be represented by the formula:

$$m^2 = \sqrt{m_{fix}^2 + m_{mark}^2 + m_{ori}^2 + m_{meas}^2} \quad (6)$$

where m_{fix} is the mean square error of the coordinates of the fixed points in the known coordinate system. The magnitude of the mark m_{mark} depends on the accuracy of determining the coordinates of the spherical signals by which georeferencing is performed; m_{ori} is the mean square error of the scanner's external orientation; m_{meas} - the mean square error of the instrument, which reflects the influence of the external environment and the metrological properties of the surface of the object.

When assessing the accuracy of georeferencing the point cloud, it is necessary to take into account the accuracy of determining the coordinates of the spherical signals in the external system. If the coordinates of the points of the support network are obtained using a total station, the errors from centering and orientation reach 3-5 mm. If the coordinates are determined by GNSS measurements, then we may have an error of up to 2 cm in the planned position and up to 5 cm in the altitude position. Depending on the task to be solved, adjustments should be made to the heights obtained from GNSS so as not to change the horizon of the measured point cloud.

Target-based point cloud registration methods cannot exploit the full potential of the data. Registration points are usually not located at the maximum measured length by the scanner and this leads to a problem with extrapolation beyond the reach of the marks and loss of accuracy. There is a strong correlation between the geometric position of the marks and the accuracy of registration. Spheres must remain stable throughout the measurement campaign. On the other hand, marks are absolutely mandatory when absolute orientation is required and in deformation applications, digital models for 3D cadastre [11] and Building Information Modelling (BIM) applications [12]. The use of spherical marks in georeferencing ground-based laser scanning data reduces the time for measurement and processing of measurements, providing accuracy commensurate with calcic geodetic measurements for cadastre, BIM and Preservation of immovable cultural heritage [9].

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