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Comparison and analysis of results of 3D modelling of complex cultural and historical objects using different types of terrestrial laser scanner

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Comparison and analysis of results of 3D modelling of complex cultural and historical objects using different types of terrestrial laser scanner

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Laser scanning does not provide unlimited geometrical accuracy and integrity when scanning complex objects. Scanning systems have a minimum and maximum range in which they operate, depending on the technical characteristics. Scanning below or above these limits results in gross errors and registering of incorrect data. Laser scanners can have difficulties with certain materials such as marble and reflective surfaces. This paper presents the results of laser scanning of a complex monument of cultural and historical heritage using two different types of terrestrial laser scanners. Afterwards, the comparison and analysis of the results are shown. The scanners used were terrestrial laser scanners Faro Focus 3D (phase mode distance measurements) and STONEX X300 (pulse mode distance measurements).

Keywords: Cultural and historical heritage, Terrestrial laser scanning, Phase scanner, Pulse scanner, Data processing, 3D model, Registration quality, Positional accuracy assessment

Introduction

The cultural heritage (cultural and historical heritage, national heritage, or just heritage) refers to the inheritance of physical artefacts and immaterial attributes of a group or society which constitutes the heritage of past generations and is carefully preserved in the present to be left in inheritance for the benefit of future generations. That kind of heritage, that has been historically preserved is often unique and irreplaceable and the responsibility for its protection lies with the next generation. It is usually under protection and has symbolic importance in the minds of people. However, from the economic aspect, it presents a significant tourist potential (Mulahusić *et al.* 2013). Documentation, bibliographic heritage and buildings, places where cultural goods are permanently stored or exhibited, are the evidence of the emergence of human spiritual creativity throughout history. The protection and preservation of cultural heritage ensure the stability of cultural values as well as the potential for further development of any country, its affirmation and better quality of life.

Documenting of the shapes and forms of cultural heritage previously consisted solely of hand drawings. The development of humankind and the progress of science made the documentation process simpler, faster and more accurate, especially through the use of photogrammetric methods of data collection. Today's surveying technologies allow collecting of large amounts of 3D data in a short period. An overview of different methods for three-dimensional digitalisation applicable in producing documentation of the objects of cultural heritage is given by (Pavlidis *et al.* 2007).

First of all, the terrestrial laser scanning method should be emphasised. It is used to capture large plaques, rural and urban areas, sea beds, facades, statues, and archaeological artefacts. Recent studies have shown that laser scanning is very useful in projects of testing the deformation of objects and soil, such as monitoring of landslides (Vilceanu *et al.* 2016). The mobile laser scanning technology can be used to capture and model large areas of cultural heritage (Rodríguez-Gonzálvez *et al.* 2017). The full power of laser scanning comes to the fore in combination with the CAD/GIS techniques, with the purpose of storing and processing the collected spatial information (Lezzerini *et al.* 2016).

The cultural and natural monuments are invaluable. This fact is often recognised when they are threatened, or even destroyed. By using 3D models, it is possible to renovate them, or at worst to reconstruct such objects of cultural heritage. Apart from the long-term digital preservation, and documentation of these monuments, it is possible to interactively present and visualise monuments using 3D models (Cetl *et al.* 2013). Different types of documents about monuments are the basis for any conservation project. Their role in the preservation of heritage has long been observed, especially in the identification, protection, interpretation, and conservation (Mulahusić

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et al. 2016). For example, the city of Vienna uses the detailed 3D model to protect its historic core. This 3D model is used, in addition to documenting the current status of protected buildings, to preserve precious views and directions in the city (Cetl *et al.* 2013). In this paper, we wanted to examine how the choice of different laser scanners (phase and pulse) and different approaches of measurement procedures and data processing influence the accuracy of the collected 3D coordinates of architectural heritage objects. Two different strategies for obtaining 3D coordinates were used in this research:

- a classic, that involves the use of artificial targets for the purpose of registering and georeferencing scans and
- the strategy that does not require artificial targets (the procedure with global navigation satellite system (GNSS) receiver within the scanner itself) and the registration, in this case, is based on natural unmarked targets.

Main goal was to examine differences in the accuracy of scanning registrations after processing data collected by above-mentioned procedures.

Basic information about the processed historical site

Marko Marulić (Split, August 18, 1450 – Split, January 5, 1524) was a Croatian writer and Christian humanist, father of Croatian literature. He was a scholar and a prolific writer, who left many literary works in his legacy. He wrote in three languages: Latin, Italian and Croatian. The most important Marulić's Croatian work is *Judith*, in which he calls for resistance to the threatening Ottoman power (Fališevac 2002).

On March 22, 1998, the monument to Marko Marulić was unveiled in Zagreb (Fig. 1). In that way, the proposition made one hundred years before by the Association of Croatian Writers had been fulfilled. Raising of the monument to Marko Marulić carries multiple meanings, the most important of which is that Zagreb and Croatia are paying tribute to one of their greatest sons appropriately. The monument symbolises in the best possible way the greatness and power of Marulić's literary work.

1 Monument to Marko Marulić in Zagreb during the scanning by Faro Focus 3D instrument

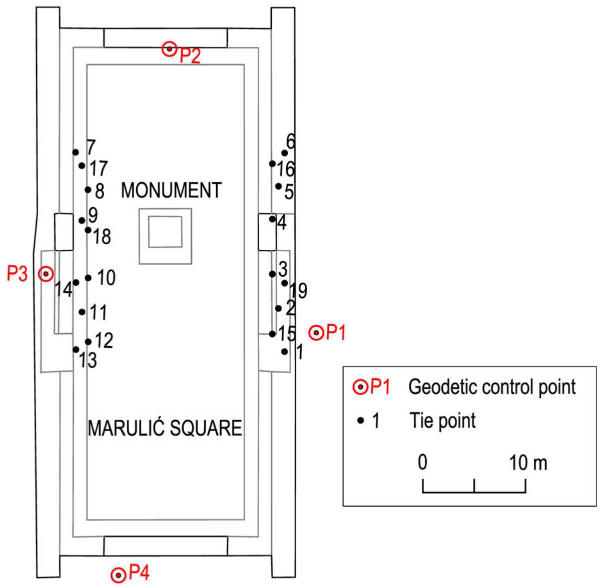
Together with the monumental sculpture that dominates the Zagreb Marulić square, a bronze plate with the verses from the poem *Judith* was placed in the central floral medallion. The Marko Marulić statue together with its stand is 7 m wide, 7 m long and 4 m high.

Fieldwork and data processing for making a 3D model

The project of geodetic network and control points

Before laser scanning, it was necessary to make a measurement plan that primarily encompasses the selection of operative polygon points and position of the terrestrial laser scanner. The ideal distance between the operative polygon points is 10 m, and after the reconnaissance in the field it was determined that five points of the operative polygon would be situated in the field. The operative polygon points, or geodetic base, were determined using the GNSS method, with the aim of georeferencing, i.e. determining the position of scans in the State Coordinate System of the Republic of Croatia. The CROatianPOSitioning System (CROPOS) was used. The measurements were carried out at the appropriate time intervals, considering the change of satellite geometry. All measurements and temporary stabilisations were performed according to the Technical Specifications for Determining Coordinate Points in the Coordinate System of the Republic of Croatia. As a result of GNSS measurements, the operative polygon coordinates were obtained in the official positional (HTRS96) and height (HVRS71) reference coordinate system, using the official HRG2009 geoid model. More details on Croatian National Reference Coordinate System are given by NSDI (2018).

To register, i.e. to merge scans from different occupation points to the whole, tie points were used. Two adjacent scenes should have at least three tie points, although five points are recommended for easier, more reliable registering of scans. For this reason, it was necessary to plan in detail the arrangement of artificial markers



2 Sketch of the scanning – the position of the operating polygon points and control points (targets)

(targets), to satisfy the condition of tie points on each scan. Targets were placed on the surrounding stairs around the monument (Fig. 2), at different heights, to register the particular scans in software easier and more accurate. In fact, if all targets are placed in the same plane, the software will not recognise all of them, and the registration of the scans will be less accurate. Coordinates of 19 artificial targets are defined in the State Coordinate System by the method of terrestrial positioning, based on measured horizontal directions, zenith angles and slope distances.

Laser scanning of objects and data processing

At the world market today there is a very diverse range of terrestrial laser scanners that are not universal for all applications but are used for different project tasks. Numerous authors compared terrestrial laser scanners and created various analyses, including several authors (San José *et al.* 2011, Chow *et al.* 2012, Golek *et al.* 2012, Becerik-Gerber *et al.* 2011), etc. It is interesting to mention that on the website (Geo-matching 2017) it is possible to compare different types of terrestrial laser scanners. At the same website it is possible to create searches based on: year of production, weight, distance measurement method, wavelength, minimum/maximum distance measurement range, uncertainty of distance measurement (constant and variable part), laser beam width, laser beam divergence, (maximum vertical and horizontal viewing angle, etc.), operating characteristics (temperature, humidity, camera, bidirectional compensator), the laser footprint at 50-m distance, intensity registration, hits per point before averaging, scanning characteristics (maximum vertical and horizontal viewing area, etc.), operating characteristics (temperature, humidity, camera, biaxial compensator), scanning time with one battery, presence of external camera, software functionality, and training possibilities for scanner operation.

In this study, two different terrestrial laser scanners of different manufacturers were tested, and the scanners were compared to each other. Terrestrial laser scanning data were collected using the Faro Focus 3D terrestrial laser scanner (with seven scans) and using the STONEX X300 terrestrial laser scanner (with five scans). The basic technical features of the scanners used are shown in Table 1. The STONEX X300 scanner is compatible with standard GNSS measuring equipment, including a GNSS port and adapter for mounting GNSS receivers, enabling direct data collection in the State Coordinate System and no extra procedure of georeferencing data is required. This is an advantage over the time spent in the field surveying and data processing. Professionals do not need to use additional equipment (total stations, reflectors) and the use of polar methods for determining coordinates of artificial markers (signals) or natural 'targets'. The procedure of scanning and georeferencing data during its processing is simplified. Data relating to the coordinates of the artificial markers, the position of the scanner, etc. are recorded in the scanned data file. There is no need to calculate the coordinates based on the measured horizontal directions, vertical angles, and slope distances, and then to import the obtained coordinates to the software package that process the scan data.

Table 1 Specifications of used terrestrial laser scanner (Faro Focus 2017, Stonex X300 Laser scanners 2017)

Laser scanner	Faro Focus 3D	STONEX X300
Distance measuring principle	Phase	Pulse
Dimension of scanning window	360° × 305°	360° × 90°
Scanning speed [pts/s]	<976 000	<40 000
Angular resolution (horizontal and vertical)	0,009°	0,0225°
Min/max measuring range [m]	0,6–120	1,6–300
Accuracy of measured distance	2 mm at 25 m	<6 mm at 50 m
<40 mm at 300 m		
Weight [kg]	5	6
CCD camera	Yes (intern)	Yes (two intern)

The scanning process of the monument was done in a shorter period of time using the STONEX X300 scanner compared to scanning with the Faro Focus 3D scanner, primarily because no artificial markers were placed, while the scanning process of the monument with the Faro Focus 3D scanner was done by using and placing artificial markers around the monuments. Artificial markers or 'targets' were not used in the scanning process with the STONEX X300 scanner, while only the natural targets were used to test the accuracy of the scanning method. Such approaches sought to examine the difference in the accuracy of scanning registrations after processing data collected by scanning using only natural targets and scanning method using artificial markers, as it was used in the scanning with the Faro Focus 3D scanner. The difference in precision of two different scanners contributes to differences in scan registration results, but in this case, this difference is minor. Faro Focus 3D provides the scanning precision of 2 mm/25 m, and STONEX X300 scanner provides the scanning precision of 3 mm/25 m.

Monument 'Marko Marulić' is composed of two parts: the figure of Marko Marulić and the pedestal. When it comes to data processing of both parts, the approach is similar. Since the surface and shape of the object are very complicated, and with uneven areas and hidden parts, data processing requires a very dense point cloud as well as a powerful software package that provides very precise and realistic results.

The first step, once data is imported, involves pre-processing data to ensure correct registering of the scan data. It implies a 3D transformation of multiple point clouds into a unique coordinate system or their merging to a single point cloud. Scanned points are recorded and stored in a coordinate system that is relative to the scanner. The origin of that coordinate system is the position in which the laser beam hits the mirror.

The registration of the scans is based on the following: Reference objects are identified by automatic identification of artificial targets. It is provided by the programme package where the coordinates of reference objects are determined, too. Based on this principle, registering of scans in the Faro SCENE software package was done when processing the data collected by the Faro Focus 3D scanner. The registration process of the data collected by the STONEX X300 scanner in the Gexcel JRC 3D Reconstructor software is based on the algorithm that identifies the natural points, or the tie points (minimum 20 000 of identified tie points according to their position, intensity and RGB-components between the two scans). One of the scans is selected as the reference cloud point since it contains the data of the monument itself and all the objects in its surroundings. Based on it, the registration of the remaining point clouds according to the above-mentioned algorithm for identifying the points was performed.

In fact, the origins of the scanner coordinate systems are in different positions, so it is necessary to determine the spatial relationship between them. This procedure is called the registration of the scans. Moreover, the step from the scanner coordinate system scan to the coordinate system of a higher order (national coordinate system) is called transformation.

Figure 3 shows the results of the main phase of scanning data collected using the Faro Focus 3D laser scanner. For the processing of the entire monument, seven point clouds (measurement data from seven laser scanner positions) were used. During the scanning, many more points were collected, but they were erased during the processing of scan data because the scanner did not scan only the monument but also its surroundings (buildings, trees, traffic signs, roads, etc.). After processing, seven individual surfaces representing 3D models of monuments were obtained. It takes 10 to 12 days for an operator who is familiar with both the appropriate programme packages and the monument to create a 3D model. Seven TINs (triangulated irregular network) were obtained from the created 3D models (Fig. 3*a*). They were joined to a single network with 160 183 triangles (Fig. 3*b*). Then, based on the photographs of the monuments that were taken on the spot, the textures were wrapped over the TIN network (Fig. 3*c*). To improve the visualisation effect, the shadows were added to the 3D model thus created (Fig. 3*d*).

Analysis of the results obtained by measuring with two terrestrial laser scanners

When assessing the scientific and practical value of the results of laser scanning, geometric (positional) accuracy is the most important criterion for evaluation. For the quantitative expression of the geometric quality of data collected by laser scanning, two criteria of accuracy are defined:

(1) Absolute accuracy that is the uncertainty of the estimated position of scenes of the scanned object in relation to the defined reference system

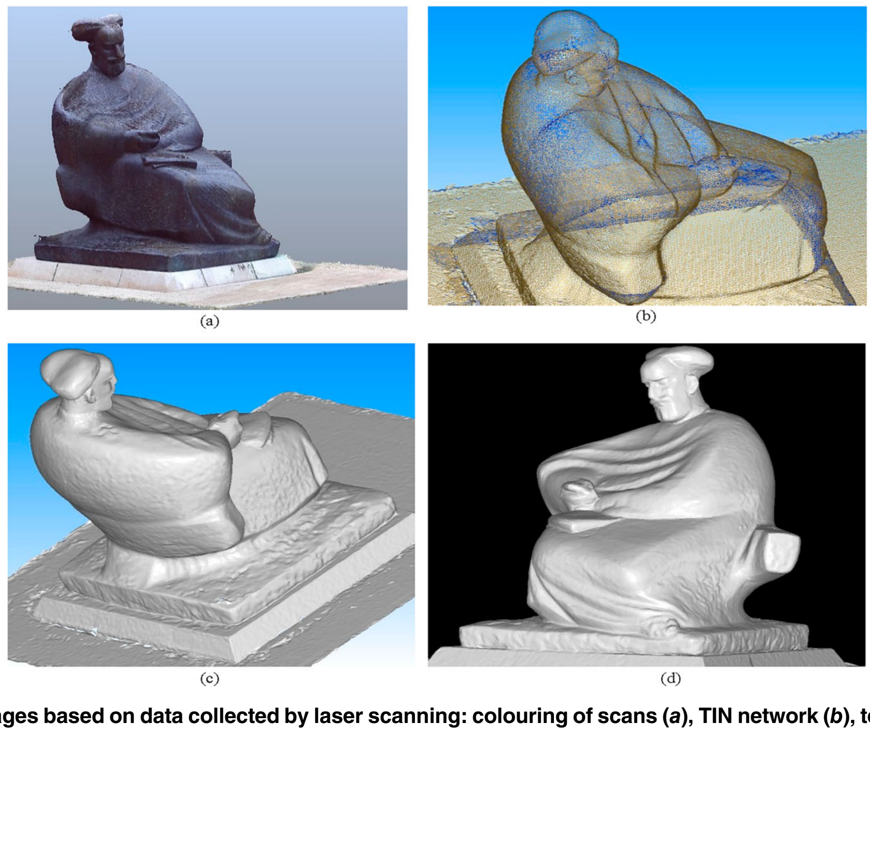
(2) Relative accuracy which represents the relative uncertainty of the position of the point relative to the other one, the directly connected adjacent point of the scanned object.

For many users, the relative accuracy is more interesting than absolute accuracy. That is why in this research local quality of laser scanning was tested, depending on the scanner and the registration method used.

The procedure for registering scans is described in detail in the previous chapter. Summaries of achieved quality of registration of scanning results in the Faro

Table 2 The registration quality of individual scans (Faro Scene)

Scan name	Standard deviation of registration [mm]
marulic001	1.6
marulic002	1.6
marulic003	2.7
marulic005	2.7
marulic006	2.2
marulic008	1.7
marulic009	1.3



3 3D modelling stages based on data collected by laser scanning: colouring of scans (*a*), TIN network (*b*), texturing (*c*), final 3D model

Table 3 The registration quality between scans (Faro Scene)

Scan name	Scan name	Standard deviation of scan fits [mm]	Amount of points with deviation <4 mm [%]	Scan overlap [%]
marulic006	marulic005	2.4	74.5	78.3
marulic008	marulic006	2.1	75.4	53.2
marulic009	marulic008	1.3	85.2	80.0
marulic005	marulic003	1.9	80.4	83.5
marulic003	marulic002	1.5	83.1	86.3
marulic002	marulic001	1.6	82.3	86.8

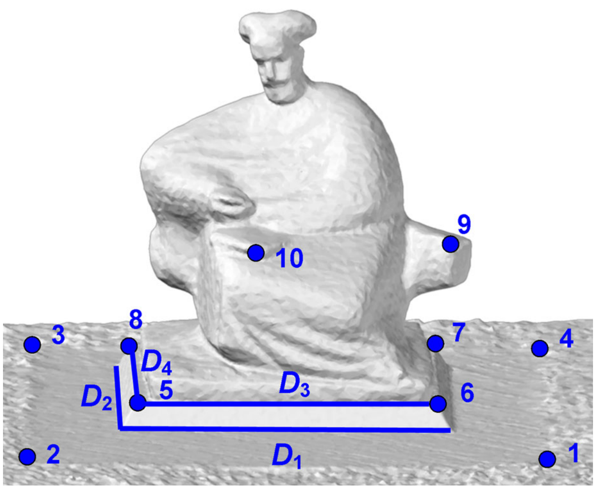
SCENE software, based on the remained deviations at the measured targets, are shown in Tables 2 and 3.

The registration of scans, i.e. scan fit shows the deviation between the surfaces and points of the scan compared with the identical surfaces and points on the adjacent scan. Scan registering based on measured targets yielded very good results which are apparent when analysing the overall standard deviation of the registration, which is approximately 2 mm, as well as the percentage of the amount of points with an overlapping error of scans lesser than 4 mm (equals 80.1% on average).

The results of the automatic processing in the software Gexcel JRC 3D Reconstructor, referring to the pre-processing – a coarse registration of point clouds and filtering, as well as the result of precise registration, namely the final registration (in relation to the reference point cloud), are shown in Table 4.

Table 4 Quality of registration between scans (3D Reconstructor)

Scan name	Standard deviation of coarse registration [mm]	Standard deviation of precise registration [mm]
Marulic1	33.9	16.9
Marulic2	29.6	14.8
Marulic3	24.4	12.2
Marulic4	28.1	14.0



4 Arrangement of control points and measured distances used to evaluate accuracy

Fine registration results show that the overall uncertainty of scans registration concerning the reference point cloud is 14.6 mm.

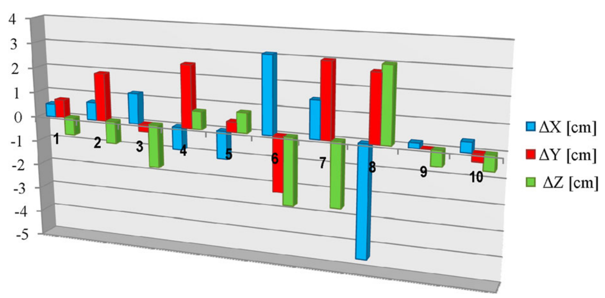
Further testing of the accuracy of the modelled object is derived by comparing the coordinates of the ten characteristic points of the monument, obtained by the analysis of the final 3D models in software packages SCENE LT and 3D Reconstructor (Fig. 4).

Table 5 gives an overview of differences between three-dimensional Cartesian coordinates of points obtained from a 3D model by software SCENE LT and 3D Reconstructor. Graphical overview of the coordinate differences is shown in Fig. 5. The obtained results show that these differences on average have large amounts, especially considering the accuracy of the scanners used (Table 1). The differences are distributed in the dispersion range that for all coordinate axes exceeds 50 mm, while the maximum individual 3D deviations of particular points reach values up to 60 mm. In the mean value analysis $\overline{\Delta Y}$ and $\overline{\Delta Z}$, according to the methodology described in (Tuno *et al.* 2015), these values are significantly different from zero, indicating that the remaining systematic laser scanning errors are present in the coordinate differences.

With the aim for a better insight into 3D model comparison results, the differences between 2D projection coordinates and altitude differences were calculated (Table 6). The analysis of the statistical indicators given in Table 6 has shown that there are significant differences in the 2D coordinates of points read on the models obtained with SCENE LT and 3D Reconstructor

Table 5 The coordinate differences of control points in the HTRS96/XYZ coordinate system (SCENE LT – 3D Reconstructor)

Control point	ΔX [mm]	ΔY [mm]	ΔZ [mm]	ΔXYZ [mm]
1	5	7	−7	11
2	7	19	−9	22
3	12	−3	−17	21
4	−9	25	7	27
5	−11	4	8	14
6	31	−22	−27	47
7	15	30	−26	42
8	−45	27	30	60
9	2	0	−6	6
10	4	−3	−6	8
Mean	1	8	−5	26
Minimum	−45	−22	−27	6
Maximum	31	30	30	60
Range	76	52	57	54
Standard deviation	20	19	18	33

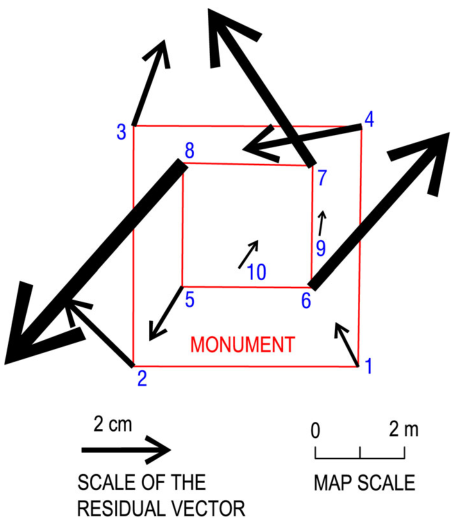


5 Graphical interpretation of 3D coordinate differences

Table 6 Coordinate differences of monument's control points in 2D coordinate system HTRS96/TMi 1D coordinate system HVRS 71 (SCENE LT – 3D Reconstructor)

Control point	Δ*E* [mm]	Δ*N* [mm]	ΔEN [mm]	Δ*H* [mm]
1	5	−10	11	0
2	17	−15	22	2
3	−6	−20	20	−5
4	26	6	27	4
5	7	12	14	−1
6	−29	−36	47	−3
7	25	−34	42	−3
8	38	47	60	−3
9	0	−6	6	−3
10	−4	−6	7	−2
Mean	8	−6	27	−2
Minimum	−29	−36	6	−5
Maximum	38	47	60	4
Range	67	83	55	9
Standard deviation	21	25	33	3

software. Large horizontal position deviations are noticeable, which amount to up to 60 mm. Since the deviations do not have the same size and direction everywhere, it was concluded that there is unhomogeneity of the 3D model of the monument. To illustrate the local geometric characteristics, a visualisation of the comparison of the model of the monument using the displacement vector graph was performed. The visual inspection reveals that there are significant changes in the orientation and intensity of the displacement vector, thus confirming previous considerations (Fig. 6). On the other hand, differences in heights are within the expected limits.



6 Vectors of positional displacement at monument's control points

As an additional indicator of the accuracy of the model, four control distances were measured on the monument, i.e. the lengths of the specific sides of the pedestal and the same length were measured in the 3D model.

The accuracy analysis was performed based on the comparison of the data obtained by direct measurement of the lengths on the monument (reference values) with the lengths between corresponding points of the 3D-model (Table 7). The directly measured distances on the monument have higher accuracy compared to distances obtained from 3D models, and they can be considered as true values. Table 7 shows that the results obtained with the SCENE LT program have approximately three times higher accuracy in relation to the 3D Reconstructor program. According to this, it can be concluded that the large differences in the control point coordinates (Tables 5 and 6) are the direct consequence of the remaining systematic errors of the scans registrations in the 3D Reconstructor program.

Conclusion

The terrestrial laser scanning, using the appropriate instrumentation and the application of an adequate methodology of data processing is an efficient technique for documentation of various monuments, which is demonstrated in this paper on the example of 'Marko Marulić' monument in Zagreb. Almost two decades have passed since the erection of the monument, during which time various weather conditions affected the monument. The greatest damages to monuments are caused by constant exposure to external influences. Every penetration of water and frost slowly damages the structure of the final layer. For this reason, it is necessary to create a reliable document that will describe all the geometric features of the mentioned monument, so that future generations can enjoy and admire the monument of the 'father of Croatian literature'. Such documentation assumes creating a 3D model of the object as a digital copy obtained from a point cloud.

To create a photorealistic 3D model that displays a certain level of accuracy, advanced data collection and processing technologies are required. Two terrestrial laser scanners, the Faro Focus 3D and the STONEX X300 were used in this data collection work. The instrument Faro Focus 3D is more suitable for projects of this type, and with an excellent internal (integrated) digital camera points out the details and can scan even at high

Table 7 Comparison of measured distances on the monument, in the 3D model obtained in SCENE LT software package and in the 3D model, obtained in 3D Reconstructor software package

Control distance *i*	Real distance on object D_i [m]	Distance in SCENE LT S_i [m]	Distance in 3D Reconstructor R_i [m]	D_i–S_i [m]	D_i–R_i [m]
1	3.191	3.196	3.186	−0.005	0.005
2	3.000	2.995	2.992	0.005	0.008
3	2.933	2.922	2.911	−0.011	0.022
4	2.740	2.741	2.713	−0.001	0.027

brightness. The STONEX X300 is a terrestrial laser scanner that contrasts with the Faro Focus 3D scanner with inferior quality of the internal digital camera. Thus, it has a lower quality of details. However, this scanner allows using an additional (external) camera to improve the detail quality.

The analysis of the obtained 3D models shows that the results of the registration of data collected by the Faro Focus 3D scanner are better than the data registration results collected by the STONEX X300 scanner. This can primarily be explained by the use of artificial targets, whose coordinates are determined by precise terrestrial positioning when registering the scans by the SCENE LT software while such targets have not been used during the data processing with the 3D Reconstructor software. The main source of big differences is the procedure (method) of registration and georeferencing of scans in the Gexcel JRC 3D Reconstructor software, which was done without artificial markers (targets). In addition to mentioned, it should be taken into account that for the purposes of the accuracy assessment, the coordinates of the control points were determined 'manually' on 3D models. The quality of such a coordinates depends on the subjective judgment of the operator, i.e. his ability to bring the cursor to the correct position, which is again associated with professional knowledge and attention at work. The difference in declared accuracy of registration with the scanner Faro and Stonex is very small, but in reality, it is drastic (especially for the STONEX scanner). The reason for this interpretation might be the amount of collected data, which is significantly larger for the FARO scanner. Since pulse scanners generally have much lower frequency of collected data comparing to phase and triangulation scanners (the difference in the speed of collecting with Faro comparing to Stonex is 20 times greater and the maximum angular resolution is 2.5 times better with Faro scanner comparing to Stonex – resulting with 2.5 ^ 2 = 6.25 times larger spatial resolution). There are also fewer points in the registration for Stonex and the registration is more uncertain and less accurate. The disposition of deviation vectors supports that conclusion.

The performed research shows a low reliability of the standard representation of 3D model accuracy obtained in the laser scanning software. Namely, the standard deviation of the registration, calculated using the residuals at the identical points, represents a poor diagnosis of the actual geometric quality of the 3D model. In this paper it is confirmed that the most reliable way of assessing the quality of spatial data is based on the use of control points, and that the real quality of the 3D model is 2–3 times worse than the one displayed by software after the point cloud registration.

The 3D model of the 'Marko Marulić' monument obtained through the scanning of the data collected by the Faro Focus 3D scanner, with the presented results of registration and processing (reliable representation of the texture of the monument) is a faithful 3D model that can be used in terms of data archiving for future restoration works. The 3D model obtained by processing of scanning data recorded by the STONEX X300 scanner, though of poorer quality, can be used to archive data for future restoration jobs in situations where there are fewer fine details. It should be noted that the recording error would be smaller and the image quality better, using an external digital camera, because the internal one (integrated with STONEX X300 scanner) is of inferior quality.

By processing data and analysing the results obtained by scanning with two different terrestrial laser scanners, we continue to confirm the thesis that 3D reconstruction by laser scanning ensures high measuring accuracy, visual availability, and efficiency. Of course, 3D view helps to keep the cultural heritage unforgettable. It serves as a communication tool not only for conservators, but also for the general public. For this reason, by enabling the availability of virtual heritage to the general public, laser scanning technology becomes a primary tool for publishing the cultural heritage.

As a solution for future work in large objects of free, asymmetrical and irregular forms, a very careful selection of the position of the occupation points of the control network is proposed, as well as recording the edge of the object with a higher spatial resolution. In the case that some parts of the object cannot be recorded from the chosen occupation points, it is suggested to set the scaffold around the object, if it is profitable. In that way, it is possible to record all hidden parts that are impossible to record from the occupation points on the ground.

Geolocation information

45°48′25,2″N 15°58′12,6″E (WGS84)

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