OCENA KAKOVOSTI LIDARJA V APPLOVIH NAPRAVAH

QUALITY ASSESSMENT OF LIDAR IN APPLE DIGITAL DEVICES*

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IZVLEČEK

Podjetje Apple je leta 2020 v svoje pametne naprave prvič vgradilo sistem senzorjev lidar. S tem je lasersko skeniranje prvič v zgodovini pristalo v rokah laičnega uporabnika. V članku preverjamo, kako se nizkocenovni lidar snemalni sistem, vgrajen v Applovo napravo, odreže v primerjavi s profesionalnim geodetskim terestričnim laserskim skenerjem. Poleg kratkega opisa delovanja merskega sistema v Applovi napravi smo opravili celovit pregled literature. Različni avtorji so obravnavali sistem v primerjavi z drugimi metodami zajema prostorskih podatkov ali v študiji uporabnosti na različnih področjih. V članku smo preverjali geometrično kakovost snemalnega sistema lidar, vgrajenega v Applovi napravi iPad Pro, za potrebe 3D-modeliranja notranjih prostorov stavb. Izvedli smo poskusa na manjšem (~1 m) in večjem (~10 m) testnem polju ter ovrednotili geometrijsko kakovost zajetih podatkov. Ugotavljamo, da sistem Apple na večjih območjih ne more zagotoviti relativne položajne točnosti, boljše od 10 cm, in je lahko uporaben zgolj za izdelavo informativnih 3D-prikazov.

ABSTRACT

In 2020, Apple incorporated a LiDAR sensor system into its smart devices, being the first to offer the laser scanning technology to the general consumer. This article investigates how a low-cost LiDAR scanning system integrated into Apple devices performs in comparison to professional geodetic terrestrial laser scanners. In addition to providing a brief overview of the functionality of the measurement system within Apple devices, a comprehensive literature review was conducted. Various authors have examined the system either in comparison to other spatial data capture methods or in studies of its applicability across different fields. In this article, we examined the geometric quality of the lidar scanning system embedded in the Apple iPad Pro device for the purpose of 3D modeling of indoor building spaces. We conducted experiments in a smaller (~1 m) and larger (~10 m) test field and evaluated the geometric quality of the captured data. The findings indicate that the Apple system cannot achieve relative positional accuracy better than 10 cm and is primarily suitable for creating informative 3D representations.

KLJUČNE BESEDE

Lidar, Apple lidar, iPhone 13 pro, iPad Pro, oblak točk, natančnost, točnost, razpršenost, lasersko skeniranje

KEY WORDS

Lidar, Apple lidar, iPhone 13 pro, iPad Pro, point cloud, precision, accuracy, dispersion, laser scanning

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* *The English translation was made with the help of ChatGPT*

1 INTRODUCTION

Terrestrial laser scanning, which captures data based on the lidar measurement system, has gained significant importance in the past decade in the field of data acquisition for geodetic purposes. Scanning equipment is relatively expensive, and the capturing process and subsequent processing require an engineering approach and some experience. Therefore, laser scanning is only used for specific tasks in geodesy, construction, archaeology, architecture, and similar fields. Laser scanning is a geodetic measurement method that captures space non-contactly with a dense polar grid. The instrument is called a laser scanner.

With the miniaturization and lowering costs of sensors and increasing processor capabilities, laser scanning is increasingly appearing in everyday life. Lidar was initially integrated into smartphones and tablets to assist with functions such as face recognition and automatic camera focusing. In 2020, Apple introduced the iPhone 13 smartphone and iPad Pro tablet, which, with the help of a lidar sensor, in addition to the above-mentioned functions, also enabled laser scanning. This brought laser scanning, as a spatial data capture process, into the hands of lay users for the first time (Whitney, 2024).

Laser scanning using a smartphone has sparked significant interest among spatial data capture professionals, mainly due to its affordability and ease of use.

In this article, we examine the geometric quality of spatial data captured by the Apple system. We are interested in the system's usability for objects ranging from 1 m to 10 m in size. For example, in measuring buildings and parts of buildings for real estate registration. For larger areas, we believe the Apple system is currently not suitable. We evaluate the quality by comparing it with the results of a geodetic terrestrial laser scanner with centimetre accuracy and known target positions in the test field.

In the introduction, we outlined the topic, described the basic principles of operation of Apple's laser scanning system, and reviewed the publications of authors who have dealt with this topic. In the next chapter, we will describe the methodology: present the measuring equipment used, the test fields on which we conducted experiments, the execution of measurements, and the methods used to evaluate the quality parameters of the recording system. In the study, we assess the accuracy and precision parameters of the measurement system, data dispersion, the influence of lighting conditions on the system's operation, and the time and work complexity of data acquisition and processing. In the third chapter, we present the test results numerically, in tables, and graphically in images. Based on the results, in the final chapter, we provide conclusions and findings.

1.1 Operation of Lidar in Apple Devices

Various free and paid applications enable us to access data captured with a lidar sensor directly, allowing us to perform laser scanning with the device. The Apple iPad device, which contains a lidar sensor (Figure 1) for distance determination, utilizes a laser implementation of VCSEL (Vertical Cavity Surface Emitting Laser) in the near-infrared spectrum.

The distance to the scanned surface is determined using either the pulsed mode or the Time of Flight (ToF) mode, where the receiver consists of a SPAD diode (Single Photon Avalanche Photodiode). The basis for distance calculation is the time it takes for the laser pulse to travel from the transmitter to the target point and back to the receiver at a known speed of light. The development of VCSEL laser sensors and SPAD diodes has significantly contributed to the integration of lidar measurement systems into smart devices (Luetzenburg et al., 2021).

Figure 1: Position of the lidar sensor in the Apple iPad Pro 2020 (source: own photograpy)

The Apple iPad Pro 2020 device captures data using the Single Photon lidar method. The VCSEL laser transmitter emits 64 laser pulses arranged in an 88 grid. The laser pulses then pass through the transmitting optics DOE (Difrective optical elements), which multiplies the input pulses by a factor of 9 and arranges them in a 33 matrix (Figure 2). Thus, in one measurement moment, the lidar sensors of the Apple device capture 576 points. The emitted pulses then return to the SPAD sensor. The entire process is repeated several times per second, with sources estimating the frequency at 15 Hz (Mandlburger et al., 2019; Plaß and Klauer, 2022).

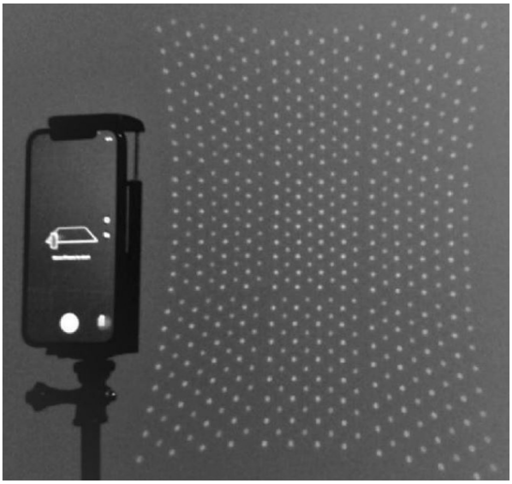

Figure 2: Point cloud grid of the lidar imaging system in the Apple iPad Pro 2020 (Source: Luetzenburg et al., 2021, license CCBY http://creativecommons.org/licenses/by/4.0/).

The Apple device captures data using the "Simultaneous Localization and Mapping" (SLAM) method. There are several implementations of the SLAM method, but we presume that the Apple device captures data using one of the "Visual SLAM" or vSLAM methods (Macario Barros et al., 2022):

- *Visual-only* method operates solely based on information obtained from 2D photographs. The device's position during data capture is determined in two ways: Feature-based, using characteristic points, and Direct methods, which determine the position based on the intensity of all pixels in the captured photograph.
- *Visual-inertial:* In addition to information from 2D photographs, this method utilizes data from IMU sensors (gyroscope, accelerometer, and magnetometer). These can be loosely or tightly coupled. With loosely coupled information, IMU sensors are used only to determine orientation and position changes, while with tightly coupled information, they are used to directly determine position.
- *RGB-D-based:* In addition to information from 2D photographs, this method also uses depth sensors.

Given that the Apple device is equipped with a lidar sensor for data capture or mapping, potentially, this sensor system could also be used to determine the device's position in real-time. This method is called lidar SLAM. We tested which of the above methods is used in the subsequent section of the article, capturing data under different lighting conditions.

Data capture with the Apple device is followed by automatic data processing. The result is a coloured point cloud, with colours added from concurrently captured photographs, which can then be exported into various formats.

The 3D Scanner App we used, allows exporting the coloured point cloud in formats such as .dxf, .ply, .las, .xyz, or .pts.

1.2 Overview of the literature

The availability of laser scanning in portable devices has sparked considerable interest in scientific circles, leading many authors to assess its utility in various research fields in different ways. Here, we will provide an overview of their results.

In the field of **3D modelling of architectural building elements or cultural heritage monitoring**, we will present four studies comparing Apple's lidar system with the photogrammetric method of 3D SFM/MVS modelling, which enables the creation of 3D point clouds or 3D models solely from photographs. Murtiyoso et al. (2021) found that the geometric quality of models captured using ground control points undoubtedly surpasses the Apple system; however, they suggest that the system could be satisfactorily useful for tasks requiring lower precision. Łabędź et al. (2022) noted that Apple's system is severely limited by its 5 m range, making it unable to measure most buildings. Teppati Losè et al. (2022) compared various scanning applications within the device. They found that the current system is limited to measuring smaller objects, but improvements could be achieved with enhancements to the SLAM algorithm. Spreafico et al. (2021), based on their tests, estimate that the Apple system is suitable for quickly capturing architectural features at a scale of 1:200 and highlight the system's ease of use and time efficiency.

The utility of the Apple iPhone 12 device for **geosciences** purposes was studied by Riquelme et al. (2021) and Luetzenburg, Kroon, and Bjørk (2021). In the first study, they focused on detecting discontinuities on rock surfaces. They compared TLS, SFM/MVS methods, and the lidar system in the iPhone 12 Pro device. Despite its limited range, they assessed the device's utility as highly promising. Luetzenburg, Kroon, and Bjørk (2021) also believe that its overall versatility in usage outweighs the limitations of its range. The Apple device is considered a cost-effective alternative to other established remote sensing techniques across various fields of application in numerous geosciences and education domains.

In the field of **manufacturing**, Vogt, Rips, and Emmelmann (2021) compared the iPad Pro and a professional industrial scanner. In industrial processes, the typical dimensions of objects are smaller compared to those in the previously mentioned fields of application. For test objects, they used LEGO bricks. They found that professional industrial 3D scanners consistently provide higher accuracy; however, for some tasks, the quality of the Apple device would suffice.

The use of laser scanning **for forestry** purposes does not require as high precision and resolution as in other aforementioned research areas. Therefore, authors who have analysed lidar in Apple devices are generally quite satisfied with the results. Gollob et al. (2021) compared the results of measuring tree trunk diameters on 21 trees using the traditional method, a handheld laser scanner ZEB HORIZON, and an Apple device. They found that measurement with the Apple device takes approximately twice as long as with the handheld laser scanner but is still two and a half times faster than the traditional method. They conclude that forest inventory with the iPad is generally feasible and enables diameter measurements with less effort than traditional approaches. Tatsumi, Yamaguchi, and Furuya (2022) developed a special application for forest inventory called "ForrestScanner" which operates on Apple devices. With its help, they managed to scan 672 trees in an area of 1 hectare in one hour and 40 minutes. The time required for measuring trunk diameters was shortened by 25% and for tree mapping by 9% compared to the traditional method. Çakir et al. (2021) successfully estimated tree diameters scanned with an Apple device with an accuracy of 2.4 cm. Their study also demonstrates that the proposed method enables mass collection of data on diameter increment and density of urban and forest trees. Similarly, Bobrowski et al. (2023) assess that lidar in Apple devices enables efficient and cost-effective tree inventory in urban areas.

Yoshida (2020) examined the operation of lidar in Apple devices **compared to other low-cost lidar sensors** on the market. He found that the device incorporates a VCSEL laser transmitter from Lumentum and a NIR CMOS receiver from Sony and described the operation of both.

Miller et al. (2021) and Kottner et al. (2023) addressed the use of the Apple lidar system for **police purposes**. The former examines its usability in capturing situations at traffic accidents. The authors note that the Apple system is significantly cheaper and easier to use. However, they also report difficulties in ensuring proper scale and other geometric errors, which are not acceptable when dealing with traffic accidents. Kottner et al. (2023) examined the quality of the Apple lidar system at crime scenes and traffic accidents. They considered two simple scenes, each involving only one object and smaller than five meters. They report fast capture (< 2 minutes), an average absolute error of 0.22 cm, and accuracy of 0.18 cm.

The usability of the Apple device for **plotting floor plans and facades** is addressed by Díaz et al. (2022). Using the example of two adjacent rooms, they assessed local accuracy, global correctness, and surface coverage provided by the system. They considered the exterior capture from the perspective of mobility and physical accessibility when capturing building entrances. Since they failed to capture more than two adjacent rooms or encountered obvious errors in larger areas, they conclude that the system is not suitable for larger areas. They estimate local accuracy at 5.3 mm, global correctness for most points below 10 cm, with some parts of ceilings and walls deviating significantly more.

King et al. (2022) examined the usability of the Apple lidar system for determining **snow cover thickness**. They scanned two selected test areas with dimensions <5 m before snowfall and then repeatedly during the winter. They report a snow cover thickness determination accuracy of 1mm, a precision of 6 mm, and a 99% correlation with ruler measurements.

Mikita et al. (2022) compared three different terrestrial laser scanning systems for **documenting forest road wear**: Faro Focus 3D, GeoSLAM ZEB Horizon, and iPhone 13 Pro. For the Apple device, they used two different applications. With the 3D Scanner app, they achieved an accuracy of 0.185 m horizontally and 0.021 m vertically, and with the Polycam app, 0.310 m and 0.045 m, respectively. They conclude that the Apple system is not accurate enough for determining forest road wear, despite achieving slightly better accuracies using processed surfaces.

Chase et al. (2022) similarly tested the Apple lidar system in a test room with precisely defined control points. In a room measuring 22.5 m x 6 m, they report achieved precisions of 3 cm and accuracies 3 cm in the horizontal direction and 7 cm in the vertical direction.

2 METHODS

In this article, we will compare the terrestrial laser scanner Leica BLK360 (Figure 3) with the lidar system built into the Apple iPad Pro 2020. We will compare their accuracy and precision, data dispersion, performance under different lighting conditions, time required for data capture, and the complexity of the work.

Figure 3: Instrument Leica BLK360 (source: own photograph).

In Table 1, we present the official technical specifications of the Leica BLK360 terrestrial laser scanner and unofficial technical specifications of the lidar recording system embedded in the Apple iPad.

Table 1: Technical specifications of Leica BLK360 and Apple iPad Pro 2020.

	BLK360	Ipad Pro 2020
Method of Length Measurement	Phase impulse WFD	Impulse
Coverage Area	360° horizontal, 300° vertical	58° horizontal, 47° vertical
Range	0.6 m - 60 m	up to 5 m
Scanning speed	360.000 points/s	576 points/measurement epoch*
Nominal precision	4 mm at 10 m, 7 mm at 20 m	Data not available

*(Plaß in Klauer, 2022) estimate that measurement frequency is 15 Hz

To compare the recording systems, we designed practical tests on two test fields. The small test field, approximately 1 m in size, is more suitable for the lidar system of the Apple device in terms of scale. Since surveying tasks in geodesy mostly cover larger areas, we also conducted tests on a larger test field measuring approximately 10 m in size.

To conduct the practical tests, we needed a reference system with higher accuracy. For this purpose, we used the Leica TS16 total station. Using the polar method, we determined the desired reference values, which in our case represent the coordinates of control and check points.

2.1 Test fields

The smaller test field consists of square wooden boxes (Figure 4), with targets marking control points (T2, T3, T6, and T8) and check points (T1, T4, T5, T7, T9, and T10). Additionally, we placed a Faro manufacturer's sphere (P12) on the test field, which we used to test dispersion.

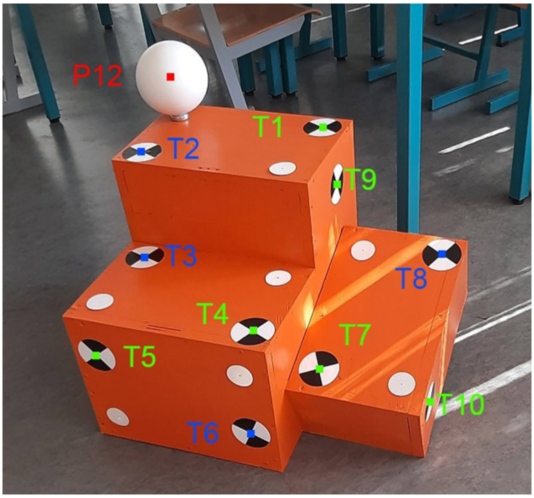

Figure 4: Smaller test field

For the larger test field, we utilized a previously established test calibration field located in the winter labs classroom in the basement of the Faculty of Civil Engineering and Geodesy (Figure 5). Here, points are also marked with black-and-white targets. We used the area with points 106, 114, 201, 205, 304, 307, 401, 408, 507, and 513 for the test field (Kregar, 2012).

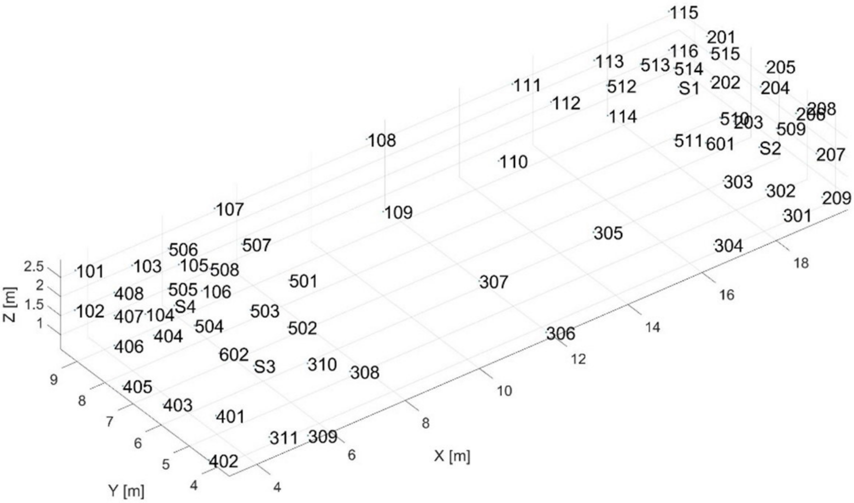

Figure 5: Control points in winter labs classroom (Kregar, 2016).

2.2 Measurements

On the smaller test field, we measured the coordinates of four reference points and six control points in the local coordinate system using the Leica TS16 instrument. We also determined the position of the centre of the sphere with a special target.

We then recorded the test field with both recording systems (Figure 6). With the Leica BLK360 scanner, measurements were taken from one position, while with the Apple iPad 2020 device, measurements were taken mobile. Based on the control points, point clouds from both systems were transformed into the local coordinate system determined by the total station. The point cloud captured with the Leica BLK360 instrument was transformed with an accuracy of 1 mm, while the point cloud from the lidar system in the Apple device was transformed with an accuracy of 11 mm.

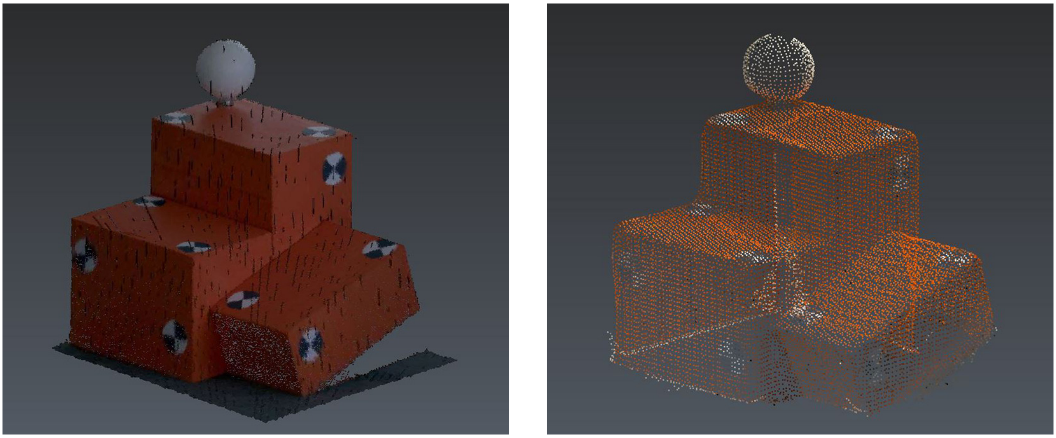

Figure 6: Results of measurements from the Leica BLK360 instrument (left) and Apple iPad Pro 2020 (right).

For the larger test field, the coordinates of the targets in the calibration field are determined in the local coordinate system in advance (Kregar, 2012). We captured the test field with both measurement methods, this time using the BLK360 scanner to capture the area from four setups (Figure 7).

Figure 7: The point cloud of the larger test field captured with the BLK360 scanner (left) and the Apple device (right).

Based on the reference points, we transformed the point cloud from the Leica BLK360 terrestrial scanner into the coordinate system of the test field with an accuracy of 2 mm.

Due to the poor resolution of the point cloud from the lidar recording system built into the Apple iPad Pro 2020, we could not perform the same transformation for these data. Therefore, we transformed the point cloud based on selected characteristic points in the BLK360 cloud. The accuracy achieved was 32 mm.

2.3 Test of position quality

The basis for determining accuracy in the smaller test field is the coordinate differences at control points ($i = 1, \dots, n$). The coordinates of the centres of the control point targets from the point clouds of Leica BLK 360 and Apple iPad were manually determined in the Leica Cyclone 3DR program. These coordinates were then subtracted from the coordinates determined with the total station, which are considered true values. The coordinate differences for each control point define the error vector: $\mathbf{e}_i$ (Cuartero et al., 2010).

$$\mathrm{e}_i = \mathrm{p}_i - \mathrm{i}_i = \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \end{bmatrix} \tag{1}$$

In this equation, represents the true coordinates of the point, and represents the measured coordinates of the point in the point cloud of each system. We also determined the overall error for each point: Δm_i (Cuartero et al., 2010).

$$\Delta m_i = \sqrt{\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2} \tag{2}$$

For the calculated coordinate differences of individual points Δx_i, Δy_i, Δz_i and overall errors Δm_i, we calculated the following statistics: mean, minimum and maximum values, standard deviation representing the estimated precision, and RMSE (Root Mean Square Error) representing the estimated accuracy.

For the larger test field, accuracy was determined based on the comparison of test planes from the point clouds of both recording systems (Figure 8). We compared the test planes in three coordinate directions. For the comparison in the direction of the x-axis, where the values of the normal vector are approximately (1, 0, 0), we used test planes 2 and 4. In the direction of the y-axis, where the values of the normal vector are approximately (0, 1, 0), we compared the recording systems based on planes 1 and 3. In the direction of the z-axis, where the values of the normal vector are approximately (0, 0, 1), we used planes 5 and 7.

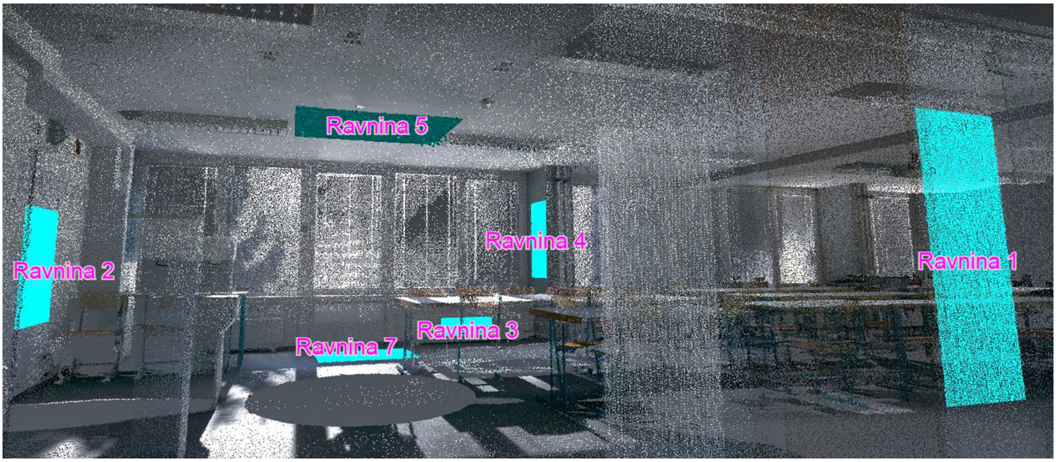

Figure 8: Display of test planes for comparison between the Apple and Leica recording systems.

Through the points of each test plane, we adjusted the plane with parameters *a*, *b*, *c* and *d*, determined by equation (3).

$$ax + by + cz - d = 0 \tag{3}$$

We then compared them and assessed differences between the point clouds captured with the Leica BLK360 instrument and the Apple iPad. We were interested in positional consistency and potential differences in the scale of the point clouds.

2.4 Measurement under different lighting conditions

We conducted this test to determine which of the SLAM registration methods the measurement system integrated into the Apple iPad Pro 2020 operates under. The test was performed only on the smaller test field, which we captured with both methods in conditions without light. If it operates based on vSLAM, it will not yield results in the dark, while lidar SLAM still allows real-time registration in the dark.

2.5 Determination of dispersion

On the smaller test field, we captured a sphere placed on the test field with both devices (Figure 9). Using the least squares method, we determined the centre and radius of the sphere from points representing the sphere in the point cloud.

For each point on the sphere, we calculated the distance to the adjusted centre of the sphere r_i. The dispersion in each set of measurements represents the standard deviation between the calculated radius r_i and the adjusted radius $\bar{\ }$.

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_i - \overline{r})^2} \tag{4}$$

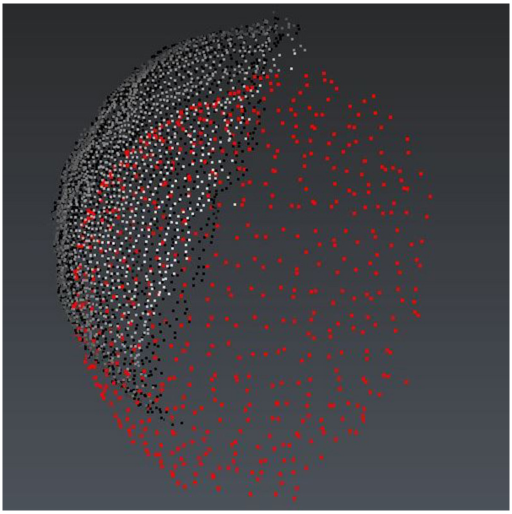

Figure 9: Faro sphere captured with Leica instrument (gray) and Apple device (red).

The value of the standard deviation (*s*) represents the dispersion of data points in the point cloud of the considered scanning system.

On the larger test field, we used test planes 1, 2, 4, 5, and 7 (Figure 9). For each plane, based on the adjusted parameters according to equation (5), we determined the distance d_i of each point from the adjusted plane. From the calculated distances, we computed the average absolute distance $\bar{d}$ using equation (6) and the standard deviation *s* using equation (7). The values of both calculated statistics represent the scatter of points around the adjusted plane, indicating the relative accuracy of the point cloud.

$$d_i = \frac{|ax_i + by_i + cz_i - d|}{\sqrt{a^2 + b^2 + c^2}} \tag{5}$$

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n} |d|_i \tag{6}$$

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (d_i - \bar{d})^2} \tag{7}$$

For all planes together, we then calculated the average value of the absolute average distance and standard deviation, thus comparing both laser scanning systems.

2.6 Time for Data Capture and Processing

We compared the time required for data capture and processing with both recording systems. We compared the time needed for data capture and registration up to the merged point cloud of each site. The comparison was conducted on both the larger and smaller test fields.

3 RESULTS

3.1 Determination of position quality

Tables 2 and 3 present statistics for deviations at control points on the smaller test field. Deviation vectors at individual control points are shown in Figure 10.

Table 2: Results of the test of position quality on a smaller test field for the Leica BLK360 instrument.

Leica BLK360	Δx [mm]	Δy [mm]	Δz [mm]	Δm [mm]
Average deviation	2.9	1.7	2.4	4.8
Maximum deviation	5.7	3.8	5.0	6.3
Minimum deviation	1.3	0.0	0.6	2.4
Standard deviation (measure of precision)	1.7	1.4	1.8	1.4
RMSE (measure of accuracy)	3.3	2.2	3.0	5.0

Table 3: Results of the test of position quality on a smaller test field for the Apple iPad Pro 2020.

Apple iPad Pro 2020	Δx [mm]	Δy [mm]	Δz [mm]	Δm [mm]
Average deviation	8.9	6.4	7.6	14.9
Maximum deviation	15.7	9.4	11.4	19.3
Minimum deviation	0.6	1.1	1.1	10.6
Standard deviation (measure of precision)	4.3	3.3	2.3	2.8
RMSE (measure of accuracy)	10.6	7.0	8.5	15.3

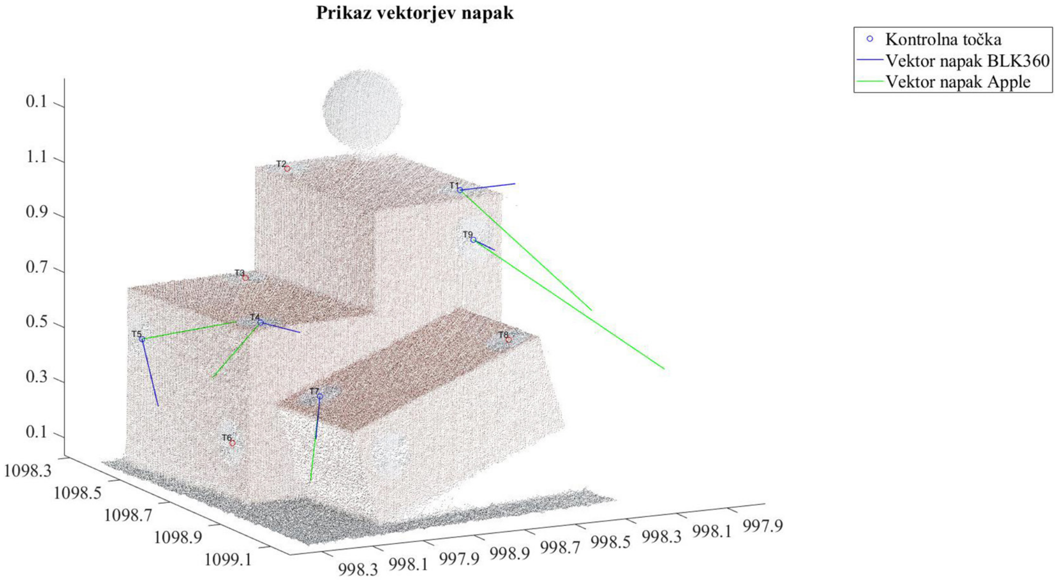

Figure 10: Display of deviation vectors at control points on the smaller test field.

In the above tables, we can see that the average modular error Δm on a smaller test field for the Leica BLK360 instrument is 4.8 mm, while for the lidar system Apple iPad Pro 2020 it is 14.9 mm. The average positional deviation of the Apple system from the terrestrial laser system is three times higher, indicating a significantly poorer precision of the results.

This is also confirmed by the accuracy measure RMSE Δm calculated using equation (2), which amounts to 5.0 mm for the Leica BLK360 device and 15.3 mm for the Apple device, which is approximately three times worse again. Similarly, in terms of precision measure, the standard deviation for the Leica BLK360 terrestrial scanner is 1.4 mm, whereas for the Apple device it is 2.8 mm.

For the larger test field, we compared planes 2 and 4 in the *x* direction (Tables 4). Their relative position can be seen in Figure 11. Table 5 also records the distance between the two test planes for data from both recording systems.

Table 4: Comparison of planes 2 and 4 captured with Leica instrument and Apple device.

	Plane 2			Plane 4		
	TLS	Apple	Difference	TLS	Apple	Difference
a [m]	1.0000	0.9997	**0.0003**	1.0000	0.9995	**0.0005**
b [m]	-0.0012	-0.0241	**0.0229**	0.0013	-0.0304	**0.0317**
c [m]	0.0005	00028	**-0.0022**	0.0038	-0.0010	**0.0048**
d [m]	19.9140	19.7599	**0.1541**	14.5598	14.4573	**0.1026**

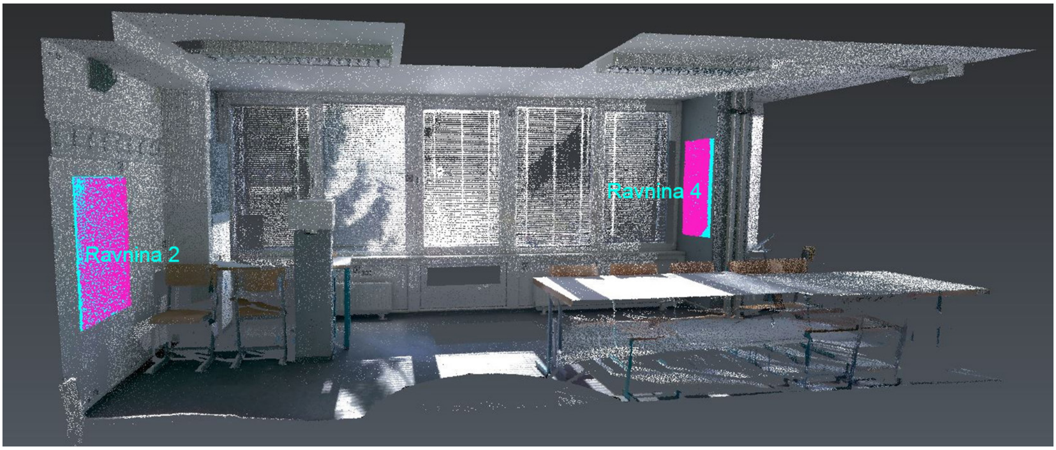

Figure 11: Position of test planes for *x* direction.

Table 5: Distance between test planes for both devices for x direction.

Direction *x*	TLS [m]	Apple [m]	Difference [m]
Distance between planes	5.3542	5.3027	**0.0515**

In the *y* direction, we compared planes 1 and 3 (Tables 6). Their relative position can be seen in Figure 12. Table 7 records the distance between the test planes for data from both recording systems.

Table 6: Comparison of planes 1 and 3 captured with Leica instrument and Apple device.

	Plane 1			Plane 3		
	TLS	Apple	Difference	TLS	Apple	Difference
a [m]	0.0080	-0.0003	**0.0083**	-0.0074	0.0197	**-0.0271**
b [m]	1.0000	0.9998	**0.0001**	0.9997	0.9998	**-0.0001**
c [m]	0.0014	0.0175	**-0.0161**	0.0239	0.0011	**0.0228**
d [m]	9.6687	9.5181	**0.1506**	3.7790	4.2570	**-0.4780**

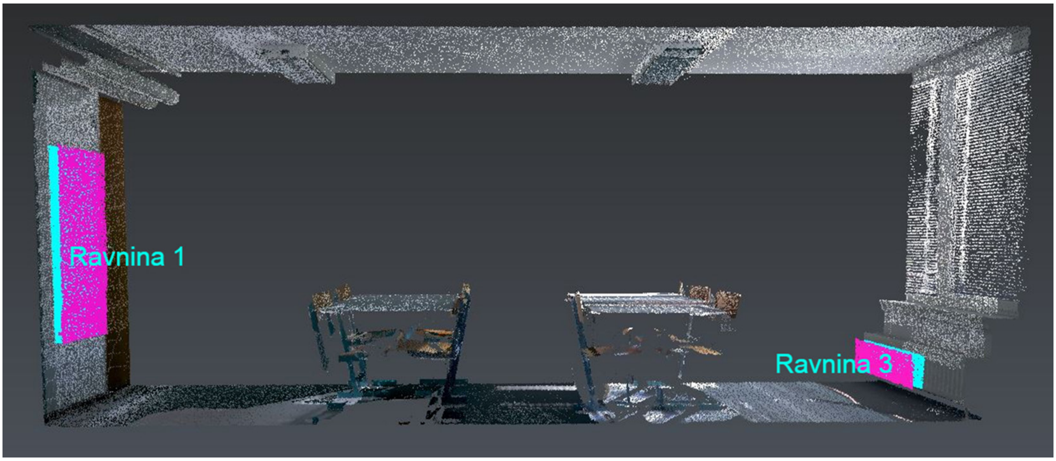

Figure 12: Position of test planes for *y* direction.

Table 7: Distance between test planes for both devices for *y* direction.

Direction *y*	TLS [m]	Apple [m]	Difference [m]
Distance between planes	5.8897	5.2611	**0.6287**

In the *z* direction, we compared planes 5 and 7 (Tables 8). Their relative position can be seen in Figure 13. Table 9 records the distance between the test planes for data from both recording systems.

Table 8: Comparison of planes 5 and 7 captured with Leica instrument and Apple device.

	Plane 5			Plane 7		
	TLS	Apple	Razlika	TLS	Apple	Razlika
a [m]	-0.0003	-0.0043	**0.0040**	-0.0017	0.0071	**-0.0089**
b [m]	0.0000	-0.0130	**0.0131**	0.0038	0.0127	**-0.0090**
c [m]	1.0000	0.9999	**0.0001**	1.0000	0.9999	**0.0001**
d [m]	2.9571	2.6867	**0.2704**	0.5550	0.7612	**-0.2061**

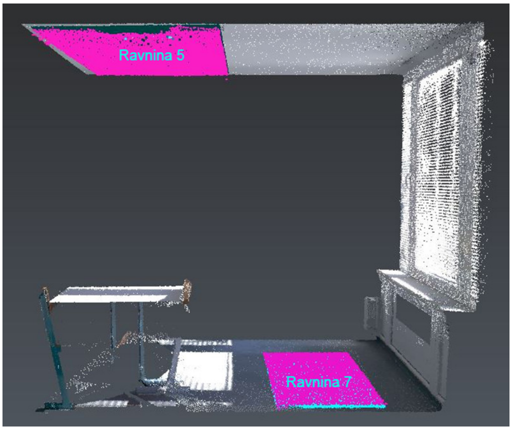

Figure 13: Position of test planes for *z* direction.

Table 9: Distance between test planes for both devices for z direction.

Direction z	TLS [m]	Apple [m]	Difference [m]
Distance between planes	2.4021	1.9255	0.4765

From the above tables, we can infer that the differences in parameters *a*, *b*, and *c* are in the range of 1 to 30 mm, which, considering the accuracy of the point cloud transformation for the Apple device, which is 32 mm, we assess as satisfactory. However, larger discrepancies occur in parameter *d*. The greatest deviation here occurs on plane 3, in the *y*-axis direction, which amounts to 478 mm. This indicates that the orientation of the planes in the point cloud of the Apple iPad Pro 2020 device is good, but larger errors occur in the position.

When comparing the lengths between the test planes in the point cloud of the Leica instrument and the Apple device in all three coordinate axes (Tables 5, 7, and 9), we observe that the lengths for the Apple iPad Pro 2020 data are consistently shorter than those for the Leica BLK360 instrument data. This finding suggests that the point cloud of the Apple device is of a smaller scale, which is also clearly illustrated in Figures 11, 12, and 13.

3.2 Determination of Dispersion

Table 10 provides the dispersions of point clouds, estimated on the smaller test field using the Faro measurement sphere, determined by equation (4).

Table 10: Presence of dispersion in measurements on the smaller test field.

	s [m]
TLS	0,0010
Apple	0,0036

The dispersion in the data from both imaging systems on the smaller test field is determined based on the presented standard deviation of the radius from each point on the sphere and the smoothed radius. For the Leica BLK360 instrument, this amounts to 1.0 mm, while for the lidar system Apple iPad Pro 2020, it is 3.6 mm. As expected, the Leica instrument provides significantly better results compared to the much cheaper Apple device.

In Table 11, we present the average absolute distances of points from the planes considered on the larger test field, along with the standard deviations of these distances for both compared measurement systems.

Table 11: Average absolute distances and standard deviations on larger test field

Average:	absolute distances for test planes	standard deviations for test planes
TLS [m]	0,0012	0,0016
Apple [m]	0,0029	0,0035

The dispersion in the point cloud of both imaging systems on the larger test field was determined based on the average absolute distance of points from the plane to the smoothed plane and the standard deviation of these distances. The average absolute distance for the Leica BLK360 instrument is 1.2 mm, while for the lidar system Apple iPad Pro 2020, it is 2.9 mm. Similarly, in terms of standard deviation, it is 1.6 mm for the Leica instrument and 3.5 mm for the Apple device. Despite yielding results nearly three times worse, considering the price, the Apple devices provide good results.

3.3 Measuring under various lighting conditions

We conducted a test on a smaller test field to determine how well Apple devices perform point cloud registration in real-time under various lighting conditions. Since the device couldn't perform measurements in the dark, we presume it likely relies on data from photographs for registration. Thus, the device probably performs registration using one of the vSLAM methods.

3.4 Execution Time

Table 12 presents the times required for capturing and processing (registering) point clouds for the two considered measurement systems. We compare the times required for experiments on both the smaller and larger test fields.

Table 12: Results of time consumption.

	Smaller test field		Larger test field	
	TLS	Apple	TLS	Apple
Data acquisition	1'5''	0'3''	8'	2'
Post-processing	5'00''	0'3''	15'	10'

Both on the smaller and larger test fields, working with the Apple iPad Pro 2020 lidar system is much simpler. As registration is performed »on the fly«, and processing is automatic after measurements are completed, professional knowledge is not required for operation. This makes it ideal for lay users of the device. The Leica BLK360 requires a bit more engineering knowledge, especially during post-processing of data. Post-processing takes more time compared to the Apple device, mainly for transferring measurement data from the instrument to the computer. Additionally, professional software and a powerful computer are required.

4 DISCUSSION

Expectedly, the instrument Leica BLK360, worth approximately 20,000 €, delivers significantly better results in terms of accuracy, precision, and dispersion on a smaller test field. On the other hand, the Apple iPad Pro 2020, valued at around 1,000 €, excels primarily in speed and ease of use. For tasks performed in areas similar in size to the smaller test field, considering its price, the Apple device yields very good results.

A similar pattern emerges on a larger test field. Although the orientation of planes is reasonably accurate with the Apple device, despite its cost, discrepancies arise in positional accuracy. Here, it's evident that the Apple device encounters difficulties with registration on larger areas, leading to inaccuracies in the final measurements. Another challenge observed with larger areas using the Apple device is its range. The device couldn't measure the entire test field, prompting us to reduce it for testing purposes (Figure 14).

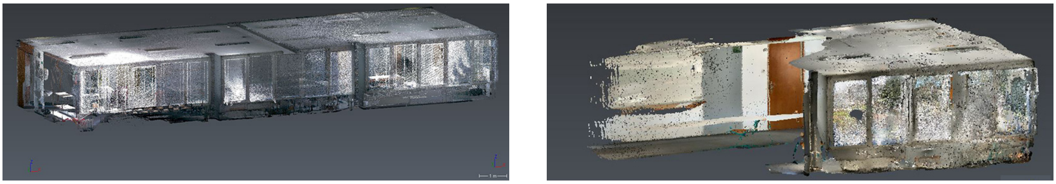

Figure 14: Point clouds of the larger test field captured with Leica BLK360 (left) and Apple device (right).

Registration issues with the Apple device also manifest as double walls on some objects (Figure 15).

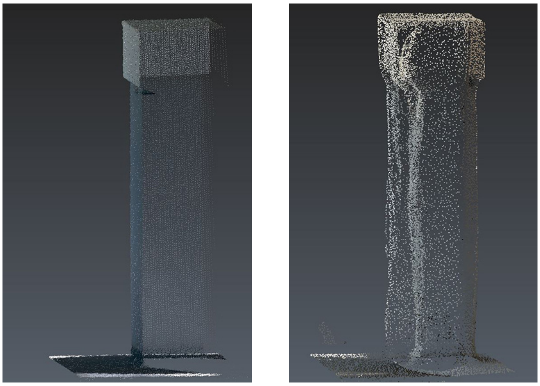

Figure 15: Comparison of point clouds detail on a larger test field measured with the Leica instrument (left) and the Apple device (right).

Differences also occur in the resolution of the lidar measurement system integrated into the Apple device compared to the Leica BLK360. The former describes spaces with fewer points, resulting in a less detailed point cloud (Figure 17).

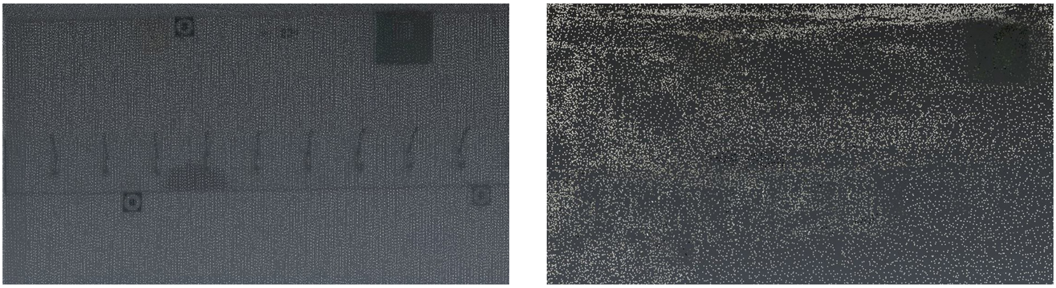

Figure 17: Section of the point cloud captured with Leica instrument.

The Apple device encounters challenges on larger areas, making it unsuitable for 3D modelling of interior spaces. Nevertheless, considering its price, it still provides satisfactory results and has potential for improvement in the future.

5 CONCLUSION

The practical test results indicate that the lidar sensor in the Apple iPad Pro 2020 currently does not achieve the desired sub-centimeter accuracy necessary for tasks involving 3D visualization or modelling of internal building spaces. However, it would be premature to deem it unusable. Lidar embedded in smart devices yields results suitable for rough spatial visualizations, virtual tours, augmented reality functions, and similar applications. Nevertheless, for demanding geodetic tasks, including 3D visualization and modelling of internal spaces, professional geodetic equipment remains indispensable.

The integration of lidar sensors into smart devices marks the beginning of a new era in spatial data capture, allowing even lay users to partake in spatial data acquisition. The development of low-cost lidar recording systems is still in its infancy, suggesting that advancements in laser diodes and microprocessors will enhance result quality over time. This trajectory could lead to cost reduction and increased popularity in the usage of 3D scanners, thereby facilitating more detailed and high-quality spatial data acquisition. However, the proliferation and cost reduction of laser scanning devices may also result in a vast amount of freely accessible detailed spatial data, which, although beneficial for tasks requiring such data, poses challenges in data quality control. Herein lies the role of geodesists, who, equipped with professional tools and engineering expertise, can ensure higher data quality and be held accountable for it.

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OCENA KAKOVOSTI LIDARJA V APPLOVIH NAPRAVAH

OSNOVNE INFORMACIJE O ČLANKU:

GLEJ STRAN 149

1 UVOD

Terestrično lasersko skeniranje, ki zajema podatke z merskim sistemom lidar, je v zadnjem desetletju pridobilo velik pomen na področju zajema podatkov za potrebe geodezije. Oprema za skeniranje je razmeroma draga, sam proces zajema in nadaljnja obdelava pa zahtevata inženirski pristop in nekaj izkušenj. Zato se lasersko skeniranje uporablja le za posebne naloge s področja geodezije, gradbeništva, arheologije, arhitekture in podobno. Lasersko skeniranje je geodetska merska metoda, ki brezkontaktno zajame prostor z gostim polarnim rastrom. Instrument, s katerim meritve opravljamo, se imenuje laserski skener.

Z miniaturizacijo in nižanjem cen senzorjev ter vse večjo zmogljivostjo procesorjev se lasersko skeniranje vse pogosteje pojavlja tudi v vsakdanjem življenju. Lidar so sprva vgrajevali v pametne telefone in tablice kot pomoč pri funkcijah prepoznave obraza in samodejnega ostrenja fotoaparata. Leta 2020 je podjetje Apple predstavilo pametni telefon Iphone 13 in tablični računalnik iPad Pro, ki sta s senzorjem lidar, poleg zgoraj naštetih funkcij, omogočala tudi lasersko skeniranje. S tem je lasersko skeniranje, kot postopek zajema prostorskih podatkov, prvič pristalo v rokah laičnega uporabnika (Whitney, 2024).

Lasersko skeniranje s pametnim telefonom je sprožilo veliko zanimanja v vrstah strokovnjakov, ki se ukvarjajo z zajemom prostorskih podatkov, predvsem zaradi cenovne dostopnosti in enostavnosti uporabe.

V članku preverjamo geometrično kakovost prostorskih podatkov, zajetih s sistemom Apple. Zanima nas uporabnost sistema na objektih, velikih od 1 m do 10 m, na primer pri izmeri stavb in delov stavb za evidentiranje nepremičnin. Menimo, da sistem Apple za zdaj še ni primeren za večja območja. Kakovost ocenjujemo na podlagi primerjave z rezultati geodetskega terestričnega laserskega skenerja s centimetrsko točnostjo ter znanimi položaji tarč v testnem polju.

V uvodu bomo orisali tematiko, opisali osnovna načela delovanja Applovega sistema laserskega skeniranja in pregledali objave avtorjev, ki so se ukvarjali s to tematiko. V naslednjem poglavju bomo opisali metodologijo: predstavili bomo uporabljeno mersko opremo, testni polji, na katerih smo izvajali poskuse, izvedbo merjenja in metode, s katerimi ovrednotimo kakovostne parametre snemalnega sistema. V raziskavi ocenjujemo parametre točnosti in natančnosti merskega sistema, razpršenosti podatkov, vpliv svetlobnih razmer na delovanje sistema ter časovno in delovno kompleksnost zajema in obdelave podatkov. V tretjem poglavju rezultate preizkusov predstavimo numerično v preglednicah in grafično na slikah. Na podlagi rezultatov v zadnjem poglavju podajamo sklepne ugotovitve in zaključke.

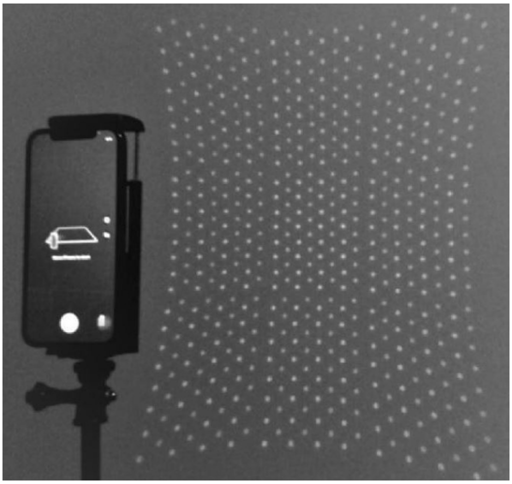
1.1 Delovanje lidarja v Applovi napravi

Različne prosto dostopne in plačljive aplikacije omogočajo, da dostopamo neposredno do podatkov, zajetih s senzorjem lidar, in tako z napravo izvajamo tudi lasersko skeniranje. Naprava Apple iPad, ki vsebuje senzor lidar (slika 1) za določanje razdalje, uporablja laser izvedbe VCSEL (*vertical-cavity surface-emitting laser*) v bližnjem infrardečem spektru.

Slika 1: Položaj senzorja lidar v napravi Apple iPad Pro 2020 (vir: lastna fotografija).

Razdalja proti skenirani površini se določa po impulznem načinu ali načinu ToF (*time of flight*), kjer je sprejemnik dioda SPAD (*single-photon avalanche photodiode*). Podlaga za izračun razdalje je čas potovanja laserskega impulza od oddajnika do ciljne točke in nazaj do sprejemnika ob znani svetlobni hitrosti. Ravno razvoj laserskih oddajnikov VCSEL in diod SPAD je najbolj pripomogel k nameščanju merskih sistemov lidar v pametne naprave (Luetzenburg in sod., 2021).

Naprava Apple iPad Pro 2020 zajema podatke po metodi single-photon lidar. Laserski oddajnik VCSEL odda 64 laserskih impulzov, razporejenih v mrežo 8 8 impulzov. Laserski impulzi nato potujejo skozi oddajno optiko DOE (*difrective optical elements*), ki za faktor 9 pomnoži vhodne impulze in jih razporedi v matriko 33 (slika 2). Tako v enem merskem trenutku lidar senzor iz naprave Apple zajame 576 točk. Oddani impulzi se nato vrnejo na senzor SPAD. Celoten postopek se ponovi večkrat na sekundo, viri ocenjujejo frekvenco na 15 Hz (Mandlburger in sod., 2019; Plaß in Klauer, 2022).



Slika 2: Raster točk lidarskega sistema Apple iPad Pro 2020 na ravni podlagi (vir: Luetzenburg in sod., 2021; na podlagi licence http://creativecommons.org/licenses/by/4.0/).

Naprava Apple registrira podatke po metodi SLAM (*simultaneous localization and mapping*). Poznamo več izvedb metode SLAM, a predvidevamo, da naprava zajema podatke po eni od metod Visual SLAM oziroma vSLAM (Macario Barros in sod., 2022):

- *Visual-only* deluje zgolj na podlagi informacij, pridobljenih iz 2D fotografij, pri tem se položaj naprave med zajemom podatkov določa na dva načina, in sicer *feature-based* oziroma na podlagi značilnih točk in *direct methods*, ki položaj določajo na podlagi intenzivnosti vseh pikslov zajete fotografije.
- *Visual-inertial* poleg informacij iz 2D fotografij uporablja informacije senzorjev IMU (žiroskop, pospeškometer in magnetometer). Te so lahko med seboj povezane ohlapno ali tesno. Pri prvih se IMU senzorji uporabljajo zgolj za določitev orientacije in spremembe položaja, pri tesno povezanih pa za neposredno določitev položaja.
- *RBG-D-based* poleg informacij 2D fotografij uporablja senzorje globine.

Glede na to, da je v napravi Apple vgrajen lidar senzor za zajem oziroma kartiranje, bi bil ta sistem senzorjev lahko potencialno uporabljen tudi za določitev položaja naprave v realnem času. Tej metodi pravimo lidar SLAM. Katero od zgoraj naštetih metod uporablja naša naprava, smo preizkusili v nadaljevanju članka, in sicer z zajemom podatkov v različnih svetlobnih razmerah.

Zajemu podatkov z napravo Apple sledi samodejna obdelava podatkov. Rezultat je oblak točk, obarvan s pravimi barvami, dodanimi iz vzporedno izdelanih fotografij, ki ga lahko nato izvozimo v različne zapise.

Aplikacija 3D Scanner App omogoča izvoz barvnega oblaka točk v formatih .dxf, .ply, .las, .xyz ali .pts.

1.2 Pregled literature

Dostopnost laserskega skeniranja v prenosnih napravah je v znanstvenih krogih vzbudila precej zanimanja, zato so številni avtorji na različne načine že ocenjevali njegovo uporabnost na različnih raziskovalnih področjih, tu bomo podali pregled njihovih rezultatov.

Na področju 3D modeliranja arhitekturnih elementov stavb oziroma spremljanja kulturne dediščine bomo predstavili štiri raziskave, pri katerih so Applov lidarski sistem primerjali s SfM-MVS fotogrametrijo, ki omogoča izdelavo 3D oblakov točk iz fotografij. Murtiyoso in sod. (2021) so ugotovili, da geometrična kakovost modelov, izdelanih z uporabo oslonilnih točk, vsekakor prekaša sistem Apple. Povzeli so, da je sistem kljub temu dovolj uporaben za naloge nižjih natančnosti. Da je Applov sistem močno omejen z dosegom le 5 metrov, so ugotovili še Łabędź in sod. (2022). Ocenjujejo, da zaradi tega z njim ni mogoče izmeriti večine stavb. Teppati Losè in sod. (2022) so primerjali različne aplikacije v napravi, ki omogočajo skeniranje. Ugotovili so, da je sistem za zdaj omejen na merjenje manjših objektov, lahko pa bi ga optimizirali z izboljšavami algoritma SLAM. Spreafico in sod. (2021) na podlagi svojih testov ocenjujejo, da je sistem Apple primeren za hiter zajem arhitekturnih značilnosti v merilu 1 : 200, pri tem izpostavijo njegovo priročnost in časovno učinkovitost.

Uporabnost naprave Apple iPhone 12 za potrebe **v geoznanostih** so preučevali Riquelme in sod. (2021) ter Luetzenburg, Kroon in Bjørk (2021). V prvi raziskavi so se ukvarjali z zaznavanjem diskontinuitet na skalni površini. Primerjali so metode TLS, SFM/MVS ter lidarskega sistema v napravi iPhone 12 Pro. Kljub omejenemu dosegu ocenjujejo uporabnost naprave kot izjemno perspektivno. Luetzenburg, Kroon in Bjørk (2021) prav tako menijo, da v skupnem vsestranskost pri uporabi prevlada nad omejitvami dosega. Naprava Apple naj bi bila stroškovno učinkovita alternativa drugim že uveljavljenim tehnikam izmer iz daljinskega zaznavanja z različnih področij uporabe v številnih geoznanostih in izobraževanju.

Na področju skeniranja **v proizvodnji** so Vogt, Rips in Emmelmann (2021) primerjali iPad Pro in profesionalni industrijski skener. V industrijskih procesih so tipične dimenzije obravnavanih objektov za velikostni razred manjše kot na prej omenjenih področjih uporabe. V raziskavi so za testne objekte uporabili kar lego kocke. Ugotovili so, da profesionalni industrijski 3D skenerji vseskozi zagotavljajo višje točnosti, kljub temu bi bila za nekatere naloge dovolj tudi kakovost Applove naprave.

Uporaba laserskega skeniranja **za potrebe gozdarstva** ne zahteva tako visoke natančnosti in ločljivosti kot na drugih opisanih področjih raziskovanja. Zato so avtorji, ki so analizirali lidar v napravah Apple, z rezultati večinoma povsem zadovoljni. Gollob in sod. (2021) so primerjali rezultate zajema obsega debel na 21 drevesih s klasičnim načinom merjenja, ročnim laserskim skenerjem ZEB HORIZON in napravo Apple. Ugotovili so, da izmera z Applovo napravo traja približno dvakrat dlje kot z ročnim laserskim skenerjem, vendar je še vedno dvainpolkrat hitrejša od klasičnega načina merjenja. Sklenejo, da je inventura gozda z iPadom na splošno izvedljiva in omogoča meritve premera debel z manj napora kot pri tradicionalnih pristopih. Tatsumi, Yamaguchi in Furuya, (2022) so izdelali posebno aplikacijo za inventarizacijo gozdov ForrestScanner, ki deluje na napravah Apple. V uri in 40 minutah jim je z njo uspelo skenirati 672 dreves na območju enega hektarja. Čas, potreben za merjenje premerov debel, so skrajšali za 25 %, za kartiranje dreves pa za 9 % v primerjavi s klasičnim načinom dela. Çakirju in sod. (2021) je uspelo oceniti premere dreves, skeniranih z napravo Apple, s točnostjo 2,4 cm. Njihova študija tudi dokazuje, da predlagani način omogoča masovno zbiranje podatkov o prirastku premera in gostoti mestnih ter gozdnih dreves. Podobno Bobrowski in sod. (2023) ocenjujejo, da lidar v napravah Apple omogoča učinkovito in cenovno ugodno inventarizacijo drevja na urbanih območjih.

Yoshida (2020) je preučeval delovanje lidarja v napravah Apple v primerjavi z **ostalimi nizkocenovnimi senzorji lidar** na trgu. Ugotovil je, da je v napravi vgrajen laserski oddajnik VCSEL podjetja Lumentum in sprejemnik NIR CMOS podjetja Sony ter opisal delovanje obeh.

Miller in sod. (2021) ter Kottner in sod. (2023) so obravnavali uporabo lidarskega sistema Apple **za potrebe policije**. Prvi obravnava njegovo uporabnost pri zajemu situacije pri prometnih nesrečah. Avtorji ugotavljajo, da je sistem Apple veliko cenejši in enostavnejši za uporabo. Vendar v zaključku poročajo tudi o težavah pri zagotavljanju pravega merila in drugih geometrijskih pogreških, ki pa pri obravnavi prometnih nesreč niso dopustni. Kottner in sod. (2023) so preučevali kakovost lidarskega sistema Apple za skeniranje prizorišč zločinov in prometnih nesreč. Obravnavali so dve preprosti prizorišči, ki vključujeta le en objekt in sta manjši od petih metrov. Poročajo o hitrem zajemu (< 2 min), povprečni absolutni napaki dolžin 0,22 cm in natančnosti 0,18 cm.

Uporabnost Applove naprave za izrise **tlorisov objektov in izrise fasad** so preučevali Díaz in sod. (2022). Na primeru dveh sosednjih sob so obravnavali lokalno natančnost, globalno pravilnost in pokritost površin, ki jo zagotavlja sistem. Zajem zunanjosti objekta obravnavajo z vidika mobilnosti zajema in fizične dostopnosti pri zajemu vhodov v objekte. Ker jim ni uspelo zajeti več kot dveh sosednjih sob oziroma so se pri večjih območjih pojavile očitne napake, ugotavljajo, da sistem ni primeren za večja območja. Lokalno natančnost ocenjujejo na 5,3 mm, globalno pravilnost pa za večino točk pod 10 cm, pri čemer nekateri deli stropov in sten odstopajo občutno več.

King, Kelly in Fletcher (2022) so preverili uporabnost lidarskega sistema Apple za **določanje debeline snežne odeje**. Dve izbrani testni območji, manjši od 5 metrov, so skenirali pred sneženjem ter nato večkrat med zimo. Poročajo o natančnosti določitve debeline snežne odeje 1 mm, točnosti 6 mm, in 99 % korelaciji z meritvami z ravnilom.

Mikita, Krausková, Hrůza, Cibulka in Patočka (2022) so za potrebe **evidentiranja obrabe gozdne ceste** primerjali tri različne sisteme terestričnega laserskega skeniranja: Faro Focus 3D, GeoSLAM ZEB Horizon in iPhone 13 Pro. Pri napravi Apple so uporabljali dve različni aplikaciji. Z aplikacijo 3D Scanner so dosegli točnost 0,185 m v horizontalnem in 0,021 m vertikalnem smislu, z aplikacijo Polycam pa 0,310 m oziroma 0,045 m. Ugotavljajo, da sistem Apple ni dovolj točen za določanje obrabe gozdnih cest, čeprav z uporabo procesiranih ploskev dosežejo nekoliko boljše točnosti.

Chase, Clarke, Hawkes, Jabari in Jakus (2022) so podobno kakor mi testirali lidarski sistem Apple v testnem prostoru z označenimi natančno določenimi kontrolnimi točkami. V prostoru dimenzije 22,5 x 6 m poročajo o doseženih natančnostih 3 cm in točnosti 3 cm v horizontalnem in 7 cm v vertikalnem smislu.

2 METODE PREIZKUSA

V prispevku bomo primerjali terestrični laserski skener Leica BLK360 (slika 3) z lidarskim snemalnim sistemom, vgrajenim v napravo Apple iPad Pro 2020. Primerjali bomo njuno natančnost in točnost, razpršenost v podatkih, delovanje v različnih svetlobnih razmerah, čas, ki ga potrebujemo za zajem, in težavnost dela.

Slika 3: Instrument Leic,5a BLK360 (vir: lastna fotografija).

V preglednici 1 predstavljamo uradne tehnične lastnosti terestričnega laserskega skenerja Leica BLK360 in neuradne tehnične specifikacije lidarskega snemalnega sistema, vgrajenega v Apple iPad.

Preglednica 1: Tehnične specifikacije instrumenta Leica BLK360 in lidarskega sistema Apple iPad Pro 2020

	BLK360	iPad Pro 2020
Način merjenja dolžine	fazno impulzni WFD	impulzni način
Območje zajema	360° horizontalno, 300° vertikalno	58° horizontalno, 47° vertikalno
Domet	0,6 m–60 m	do 5 m
Hitrost zajema	360.000 točk/s	576 točk/merski trenutek*
Nazivna natančnost	4 mm pri 10 m, 7 mm pri 20 m	ni podatka

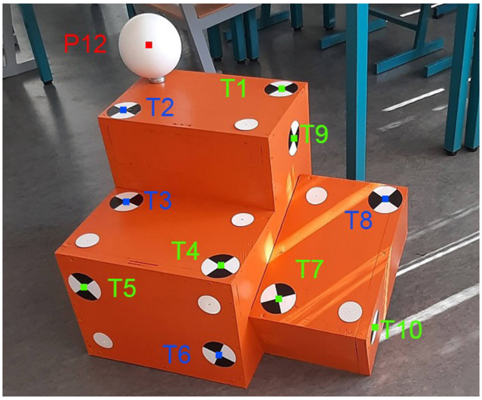
*Plaß in Klauer (2022) ocenjujejo, da je frekvenca zajema 15 Hz.

Za primerjavo snemalnih sistemov smo zasnovali praktične preizkuse na dveh testnih poljih. Malo testno polje, veliko približno 1 meter, po obsegu bolj ustreza lidarskemu sistemu naprave Apple. Ker v geodeziji dela potekajo večinoma na večjem območju, smo preizkuse izvedli še na večjem testnem polju dimenzije približno 10 metrov.

Za izvedbo praktičnih preizkusov smo potrebovali referenčni sistem, določen z višjo točnostjo. Za določitev smo uporabili tahimeter Leica TS16. S polarno metodo smo določili želene referenčne vrednosti, ki v našem primeru predstavljajo koordinate oslonilnih in kontrolnih točk.

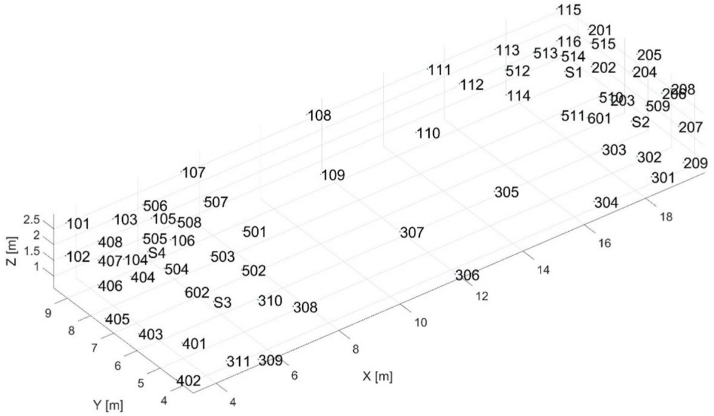
2.1 Testni polji

Manjše testno polje je sestavljeno iz kvadrastih lesenih škatel (slika 4), na katerih so s tarčami označene oslonilne točke (T2, T3, T6 in T8) in kontrolne točke (T1, T4, T5, T7, T9 in T10). Na testno polje smo namestili tudi kroglo proizvajalca Faro (P12) in jo uporabili za preizkus razpršenosti.



Slika 4: Manjše testno polje.

Za večje testno polje smo uporabili že vzpostavljeno testno kalibracijsko polje v učilnici za zimske vaje v kletnih prostorih Fakultete za gradbeništvo in geodezijo (slika 5). Tudi tukaj so točke označene s črno-belimi tarčami. Za testno polje smo uporabili območje s točkami 106, 114, 201, 205, 304, 307, 401, 408, 507 in 513 (Kregar, 2012).

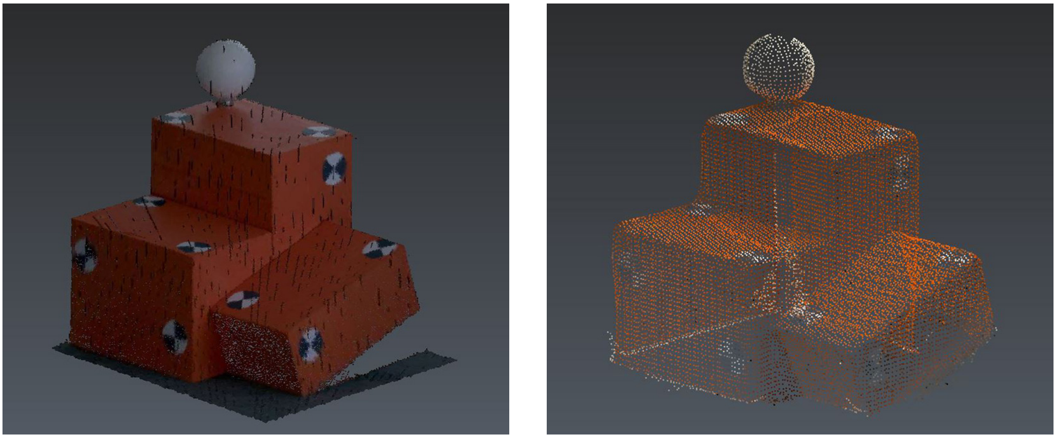


Slika 5: Prikaz položajev oslonilnih točk v učilnici za zimske vaje (Kregar, 2016).

2.2 Izvedba meritev

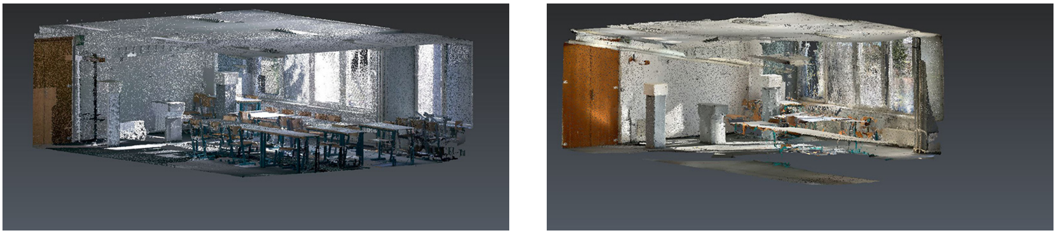
Na manjšem testnem polju smo izmerili koordinate štirih oslonilnih in šestih kontrolnih točk v lokalnem koordinatnem sistemu z instrumentom Leica TS16. S posebno tarčo smo določili tudi položaj središča krogle.

Testno polje smo nato posneli z obema snemalnima sistemoma (slika 6). S skenerjem Leica BLK360 smo izvedli meritve z enega stojišča, medtem ko smo z napravo Apple iPad 2020 meritve izvedli mobilno. Na podlagi kontrolnih točk smo oblaka točk obeh sistemov transformirali v lokalni koordinatni sistem, določen s tahimetrijo. Oblak točk, zajet z instrumentom Leica BLK360, je bil transformiran s točnostjo 1 mm, oblak točk lidarskega sistema v napravi Apple pa s točnostjo 11 mm.



Slika 6: Rezultat meritev instrumenta Leica BLK360 (levo) in Apple iPad Pro 2020 (desno).

Pri večjem testnem polju so koordinate tarč kalibracijskega polja prehodno določene v lokalnem koordinatnem sistemu (Kregar, 2012). Testno polje smo zajeli z obema metodama izmere, tokrat smo s skenerjem BLK360 zajeli območje s štirih stojišč (slika 7).



Slika 7: Oblak večjega testnega polja, zajet s skenerjem BLK360 (levo) in napravo Apple (desno).

Na podlagi oslonilnih točk smo oblak točk terestričnega skenerja Leica BLK360 transformirali v koordinatni sistem testnega polja s točnostjo 2 mm.

Zaradi slabe ločljivosti oblaka točk lidar snemalnega sistema, vgrajenega v napravo Apple iPad Pro 2020, vklopa nismo mogli narediti na enak način. Zato smo oblak točk transformirali na podlagi izbranih značilnih točk v oblaku. Točnost je znašala 32 mm.

2.3 Preizkus položajne kakovosti

Podlaga za določitev točnosti pri manjšem testnem polju so koordinatne razlike na kontrolnih točkah ($i = 1, ..., n$). Koordinate centrov tarč kontrolnih točk iz oblakov točk Leica BLK 360 in Apple iPad smo določili ročno v programu Leica Cyclone 3DR. Nato smo jih odšteli od koordinat, določenih s tahimetrom, ki jih obravnavamo kot prave vrednosti. Koordinatne razlike za vsako kontrolno točko določajo vektor napake: e_i (Cuartero in sod., 2010).

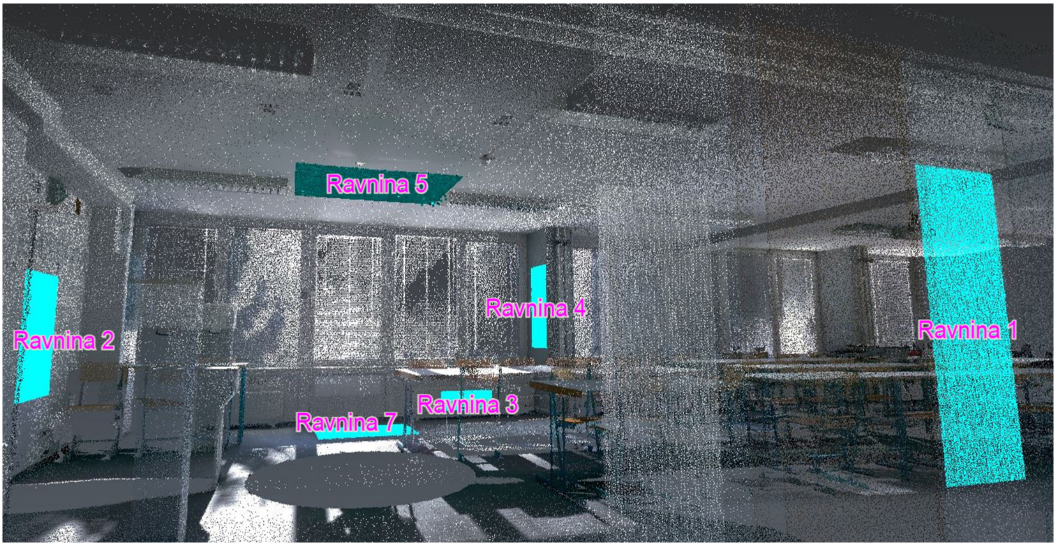
$$\mathbf{e}_i = \mathbf{p}_i - \mathbf{i}_i = \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \end{bmatrix} \tag{1}$$

Pri enačbi so p_i prave koordinate točke, i_i pa izmerjene koordinate točke v oblaku točk posameznega sistema. Določili smo tudi skupno napako za vsako točko: Δm_i (Cuartero in sod, 2010).

$$\Delta m_i = \sqrt{\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2} \tag{2}$$

Za izračunane koordinatne razlike posameznih točk Δx_i, Δy_i, Δz_i in skupne napake Δm_i smo izračunali naslednje statistike: povprečje, minimalno in maksimalno vrednost, standardni odklon, ki predstavlja ocenjeno natančnost, ter koren srednjega kvadratnega pogreška (RMSE), ki predstavlja ocenjeno točnost.

Pri večjem testnem polju smo natančnost določali s primerjavo testnih ravnin iz oblakov točk obeh snemalnih sistemov (slika 8). Testne ravnine smo med seboj primerjali v treh koordinatnih smereh. Za primerjavo v smeri koordinatne osi *x*, kjer so vrednosti normalnega vektorja približno (1, 0 ,0), smo uporabili testni ravnini 2 in 4. V smeri koordinatne osi *y*, kjer so vrednosti normalnega vektorja približno (0,1,0), smo snemalna sistema primerjali na podlagi ravnin 1 in 3. V smeri koordinatne osi *z*, kjer so vrednosti normalnega vektorja približno (0,0,1), smo uporabili ravnini 5 in 7.



Slika 8: Prikaz testnih ravnin za primerjavo med snemalnim sistemoma podjetja Apple in Leica.

Skozi točke vsake testne ravnine smo izravnali ravnino s parametri a, b, c in d, ki jih določa enačba (3). Te smo nato med seboj primerjali in ugotavljali razlike med oblakoma točk, zajetima z instrumentom Leica BLK360 in Apple iPad. Zanimala sta nas položajna skladnost in morebitna razlika v merilu oblaka točk.

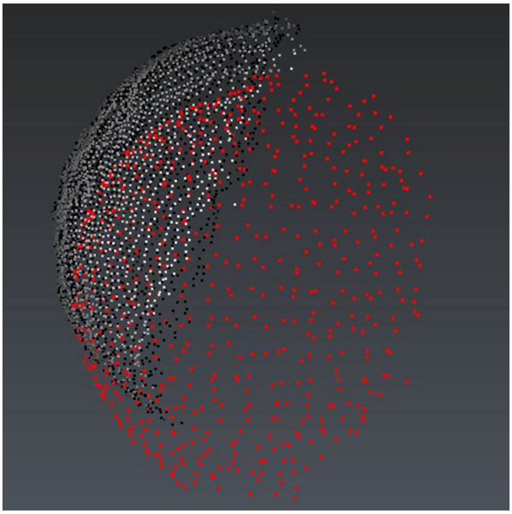
$$ax + by + cz - d = 0 \tag{3}$$

2.4 Merjenje v različnih svetlobnih razmerah

Ta preizkus smo izvedli, da bi preverili, po kateri od SLAM metod registracije deluje merski sistem, vgrajen v napravo Apple iPad Pro 2020. Preizkus smo izvedli le na manjšem testnem polju, ki smo ga z obema metodama zajema posneli še v razmerah brez svetlobe. Če deluje po metodi vSLAM, v temi ne bo dal rezultatov, medtem ko metoda lidar SLAM v temi še vedno omogoča registracijo v realnem času.

2.5 Določitev razpršenosti

Na manjšem testnem polju smo kroglo, nameščeno na testno polje, posneli z obema napravama (slika 9). Z izravnavo po metodi najmanjših kvadratov smo iz točk, ki v oblaku točk predstavljajo kroglo, določili središče in radij krogle.



Slika 9: Krogla podjetja Faro, zajeta z instrumentom Leica (sivo) in napravo Apple (rdeče).

Za vsako točko na krogli smo izračunali oddaljenost do izravnanega središča krogle r_i. Razpršenost v posameznem sklopu meritev predstavlja standardni odklon med posameznim izračunanim radijem r_i in izravnanim radijem r.

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(r_i - r)^2} \tag{4}$$

Vrednost standardnega odklona predstavlja razpršenost podatkov v oblaku točk obravnavanega snemalnega sistema.

Na večjem testnem polju smo uporabili testne ravnine 1, 2, 4, 5 in 7 (slika 9). Za vsako ravnino smo na podlagi izravnanih parametrov po enačbi (5) določili oddaljenost d_i posamezne točke od izravnane ravnine. Iz izračunanih oddaljenosti smo po enačbi (6) izračunali povprečno absolutno oddaljenost $\overline{d}$ in po enačbi (7) standardni odklon *s*. Vrednosti obeh izračunanih statistik predstavljata razpršenost točk okrog izravnane ravnine, ki pomeni relativno natančnost oblaka točk.

$$d_i = \frac{\left| ax_i + by_i + cz_i - d \right|}{\sqrt{a^2 + b^2 + c^2}} \tag{5}$$

$$\overline{d} = \frac{1}{n} \sum_{i=1}^{n} \left| d_i \right| \tag{6}$$

$$s = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (d_i - \overline{d})} \tag{7}$$

Za vse ravnine skupaj smo nato izračunali še povprečno vrednost absolutne povprečne oddaljenosti in standardnega odklona ter tako primerjali oba sistema laserskega skeniranja.

2.6 Čas zajema in obdelave podatkov

Primerjali smo čas, ki ga potrebujemo za zajem in obdelavo podatkov z obema snemalnima sistemoma. Govorimo o času, potrebnem za zajem in registracijo do združenega oblaka točk posameznega delovišča. Primerjavo smo izvedli na večjem in manjšem testnem polju.

3 REZULTATI

3.1 Določitev položajne kakovosti

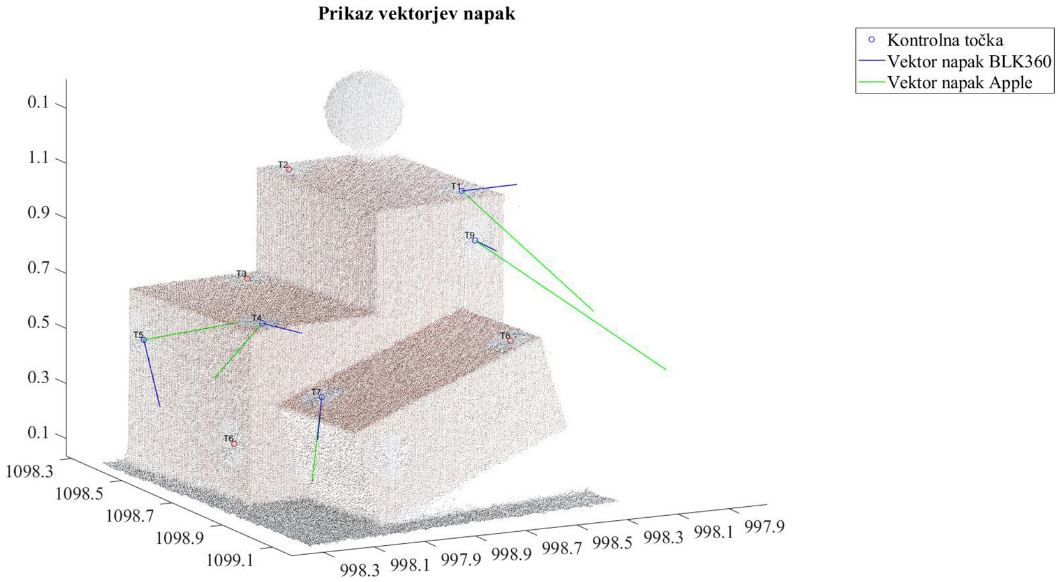
V preglednicah 2 in 3 prikazujemo statistike za odstopanja na kontrolnih točkah manjšega testnega polja. Vektorji odstopanj na posamezni kontrolni točki so prikazani na sliki 10.

Preglednica 2: Rezultati preizkusa položajne kakovosti na manjšem testnem polju za instrument Leica BLK360

Leica BLK360	Δ*x* [mm]	Δ*y* [mm]	Δ*z* [mm]	Δm [mm]
Povprečno odstopanje	2,9	1,7	2,4	4,8
Maksimalno odstopanje	5,7	3,8	5,0	6,3
Minimalno odstopanje	1,3	0,0	0,6	2,4
Standardni odklon (mera natančnosti)	1,7	1,4	1,8	1,4
RMSE (mera točnosti)	3,3	2,2	3,0	5,0

Preglednica 3: Rezultati preizkusa položajne kakovosti na manjšem testnem polju za napravo Apple iPad Pro 2020

Apple iPad Pro 2020	Δx [mm]	Δy [mm]	Δz [mm]	Δm [mm]
Povprečno odstopanje	8,9	6,4	7,6	14,9
Maksimalno odstopanje	15,7	9,4	11,4	19,3
Minimalno odstopanje	0,6	1,1	1,1	10,6
Standardni odklon (mera natančnosti)	4,3	3,3	2,3	2,8
RMSE (mera točnosti)	10,6	7,0	8,5	15,3



Slika 10: Prikaz vektorjev odstopanj na kontrolnih točkah manjšega testnega polja.

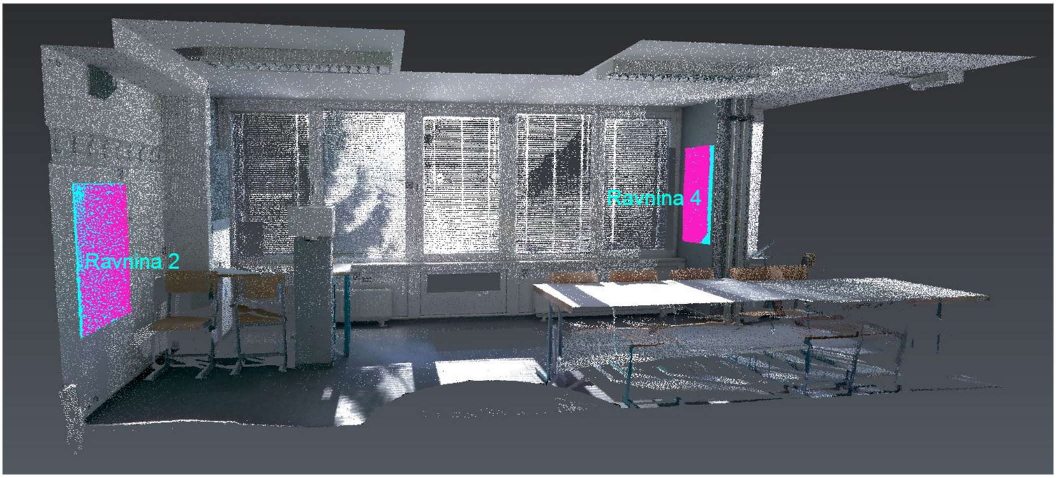
V zgornjih preglednicah lahko vidimo, da povprečna modularna napaka Δm na manjšem testnem polju za instrument Leica BLK360 znaša 4,8 mm, medtem ko je pri lidarskem sistemu Apple iPad Pro 2020 14,9 mm. Povprečno položajno odstopanje sistema Apple je kar trikrat višje od terestričnega laserskega sistema, kar nakazuje na občutno slabšo točnost rezultatov.

To nam potrjuje tudi mera točnosti RMSE Δm, izračunana po enačbi (2), ki za Leica BLK360 znaša 5,0 mm, za napravo podjetja Apple pa 15,3 mm, kar je spet približno trikrat slabše. Podobno je pri meri natančnosti, kjer standardni odklon za terestrični skener Leica BLK360 znaša 1,4 mm, za napravo Apple pa 2,8 mm.

Pri večjem testnem polju smo v smeri x primerjali ravnini 2 in 4 (preglednica 4). Njun medsebojni položaj lahko vidimo na sliki 11. V preglednici 5 je zapisana tudi razdalja med obema testnima ravninama za podatke obeh snemalnih sistemov.

Preglednica 4: Primerjava ravnin 2 in 4, zajetih z instrumentom Leica in napravo Apple.

	Ravnina 2			Ravnina 4		
	TLS	Apple	Razlika	TLS	Apple	Razlika
a [m]	1,0000	0,9997	**0,0003**	1,0000	0,9995	**0,0005**
b [m]	-0,0012	-0,0241	**0,0229**	0,0013	-0,0304	**0,0317**
c [m]	0,0005	0,0028	**-0,0022**	0,0038	-0,0010	**0,0048**
d [m]	19,9140	19,7599	**0,1541**	14,5598	14,4573	**0,1026**



Slika 11: Položaj ravnin v smeri osi *x*.

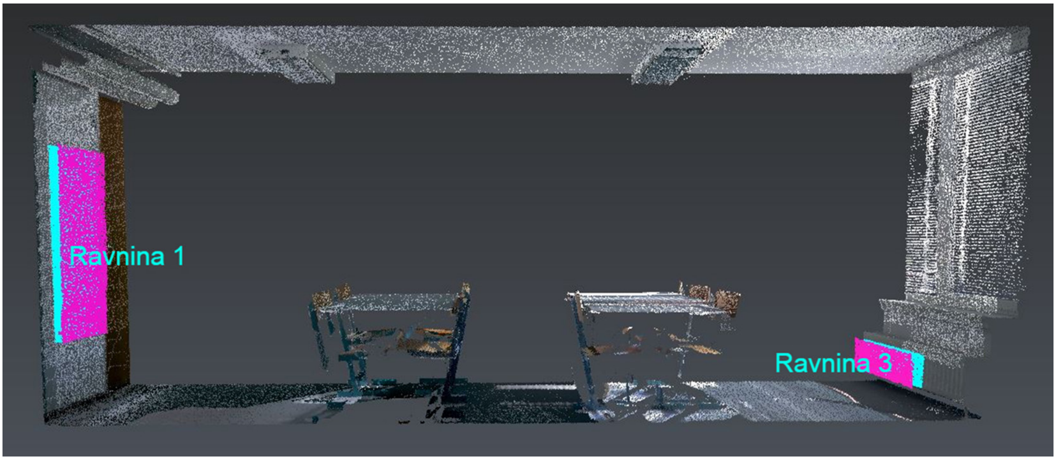
Preglednica 5: Razdalja med testnima ravninama za podatke obeh naprav

Smer *x*	TLS [m]	Apple [m]	Razlika [m]
Razdalja med ravninama	5,3542	5,3027	**0,0515**

V smeri *y* smo primerjali ravnini 1 in 3 (Preglednica 6). Njun medsebojni položaj lahko vidimo na Sliki 12. V Preglednici 7 je zapisana tudi razdalja med testnima ravninama za podatke obeh snemalnih sistemov.

Preglednica 6: Primerjava ravnin 1 in 3, zajetih z instrumentom Leica in napravo Apple

	Ravnina 1			Ravnina 3		
	TLS	Apple	Razlika	TLS	Apple	Razlika
a [m]	0,0080	-0,0003	**0,0083**	-0,0074	0,0197	**-0,0271**
b [m]	1,0000	0,9998	**0,0001**	0,9997	0,9998	**-0,0001**
c [m]	0,0014	0,0175	**-0,0161**	0,0239	0,0011	**0,0228**
d [m]	9,6687	9,5181	**0,1506**	3,7790	4,2570	**-0,4780**



Slika 12: Položaj ravnin v smeri osi *y*.

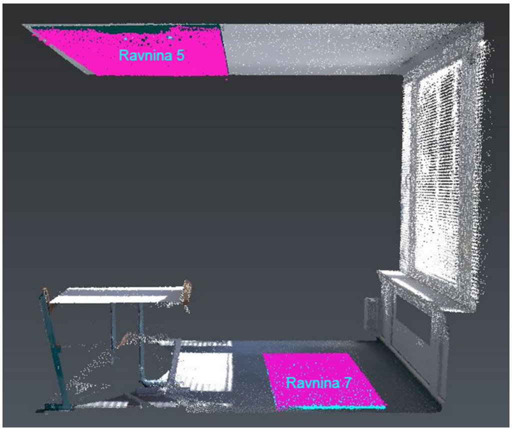
Preglednica 7: Razdalje med testnima ravninama za podatke obeh naprav

Smer *y*	TLS [m]	Apple [m]	Razlika [m]
Razdalja med ravninama	5,8897	5,2611	**0,6287**

V smeri z smo primerjali ravnini 5 in 7 (preglednica 8). Njun medsebojni položaj lahko vidimo na sliki 13. V preglednici 9 je zapisana razdalja med testnima ravninama za podatke obeh snemalnih sistemov.

Preglednica 8: Primerjava ravnin 5 in 7, zajetih z instrumentom Leica in napravo Apple

	Ravnina 5			Ravnina 5		
	TLS	Apple	Razlika	TLS	Apple	Razlika
a [m]	-0,0003	-0,0043	**0,0040**	-0,0017	0,0071	**-0,0089**
b [m]	0,0000	-0,0130	**0,0131**	0,0038	0,0127	**-0,0090**
c [m]	1,0000	0,9999	**0,0001**	1,0000	0,9999	**0,0001**
d [m]	2,9571	2,6867	**0,2704**	0,5550	0,7612	**-0,2061**



Slika 13: Položaj ravnin v smeri osi *z*.

Preglednica 9: Razdalja med testnima ravnina za podatke, zajete z obema napravama

Smer *z*	TLS [m]	Apple [m]	Razlika [m]
Razdalja med ravninama	2,4021	1,9255	0,4765

Iz zgornjih preglednic lahko razberemo, da so razlike v parametrih *a, b* in *c* velikosti od 1 do 30 mm, kar ob upoštevanju točnosti transformacije oblaka točk Apple, ki znaša 32 mm, ocenjujemo kot dobro. Do večjih odstopanj pride pri parametru *d*. Največje odstopanje tukaj se pojavi na ravnini 3, v smeri osi y, ki znaša 478 mm. To pomeni, da je usmerjenost ravnin v oblaku točk naprave Apple iPad Pro 2020 dobra, do večjih napak pa pride pri položaju. Če primerjamo dolžine med testnima ravninama v oblaku točk instrumenta Leica in naprave Apple v vseh treh koordinatnih oseh (preglednice 5, 7 in 9), opazimo, da so dolžine za podatke naprave Apple iPad Pro 2020 povsod krajše kakor v podatkih instrumenta Leica BLK360. Ta ugotovitev pomeni, da je oblak točk naprave Apple manjšega merila, kar je nazorno prikazano tudi na slikah 11, 12 in 13.

3.2 Določitev razpršenosti

V preglednici 10 sta podani razpršenosti oblakov točk, ocenjeni **na manjšem testnem polju** z mersko kroglo Faro, ki sta določeni po enačbi (4).

Preglednica 10: Prisotnost razpršenosti v meritvah na manjšem testnem polju

	s [m]
TLS	0,0010
Apple	0,0036

Razpršenost v podatkih obeh snemalnih sistemov na manjšem testnem polju je določena na podlagi predstavljenega standardnega odklona radija od posamezne točke na krogli in izravnanega radija. Ta za instrument Leica BLK360 znaša 1,0 mm, za lidarski sistem Apple iPad Pro 2020 pa 3,6 mm. Pričakovano daje instrument Leica veliko boljše rezultate od veliko cenejše naprave Apple.

V preglednici 11 podajamo povprečne absolutne oddaljenosti točk od ravnin, obravnavanih **na večjem testnem polju**, ter standardne deviacije teh oddaljenosti za oba primerjana merska sistema.

Preglednica 11: Povprečna absolutna oddaljenost na večjem testnem polju

Povprečje:	povprečne absolutne oddaljenosti od testne ravnine	standardni odklon od testne ravnine
TLS [m]	0,0012	0,0016
Apple [m]	0,0029	0,0035

Razpršenost v oblaku točk obeh snemalnih sistemov na večjem testnem polju smo določili na podlagi povprečne absolutne oddaljenosti točk ravnine od izravnane ravnine in standardnega odklona teh oddaljenosti. Povprečna absolutna oddaljenost za instrument Leica BLK360 znaša 1,2 mm, za lidarski sitem Apple iPad Pro 2020 pa 2,9 mm (preglednica 11). Podobno je pri standardnem odklonu, kjer ta za instrument Leica znaša 1,6 mm, pri napravi Apple pa 3,5 mm. Kljub skoraj trikrat slabšim rezultatom daje naprave Apple ob upoštevanju cene dobre rezultate.

3.3 Merjenje v različnih svetlobnih razmerah

Preizkus izvajanja meritev v različnih svetlobnih razmerah smo na manjšem testnem polju izvedli, da ugotovimo, kako naprava Apple izvaja registracijo oblaka točk v realnem času. Ker naprava meritev v temi ni mogla izvesti, menimo, da za registracijo najbrž potrebuje podatke iz fotografij. Registracijo naprava torej najverjetneje izvaja po eni izmed metod vSLAM.

3.4 Čas izvedbe

V preglednici 12 podajamo čase, potrebne za zajem in obdelavo (registracijo) oblakov točk za obravnavana merska sistema. Primerjamo čase, potrebne pri poskusih na manjšem in večjem testnem polju.

Preglednica 12: Rezultati časovne potratnosti na manjšem testnem polju

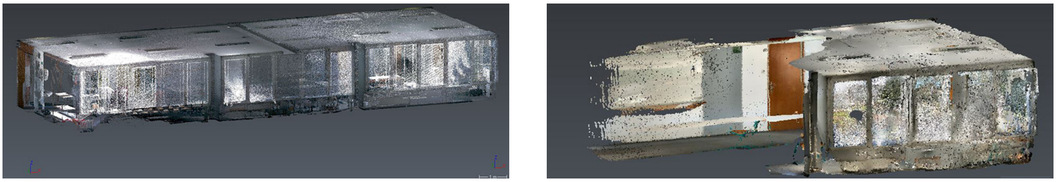
	Manjše testno polje		Večje testno polje	
Postopek	čas TLS	čas Apple	čas TLS	čas Apple
Izvedba meritev	1'50''	0'30''	8'	2'
Naknadna obdelava	5'00''	0'30''	15'	10'

Na manjšem in večjem testnem polju je delo veliko enostavnejše z lidarskim sistemom Apple iPad Pro 2020. Ker se registracija izvaja »on the fly«, obdelava pa je po končanih meritvah samodejna, za delo ne potrebujemo profesionalnega znanja. To je kot nalašč za laične uporabnike naprave. Leica BLK360 zahteva nekaj več inženirskega znanja, predvsem pri naknadni obdelavi podatkov. Naknadna obdelava vzame v primerjavi z napravo Apple več časa, predvsem za prenos merskih podatkov z instrumenta na računalnik. Zahtevana je tudi profesionalna programska oprema in zmogljiv računalnik.

4 RAZPRAVA

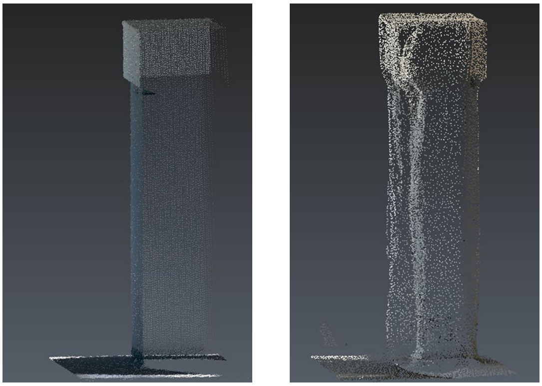
Približno 20.000 evrov vreden instrument Leica BLK360 pričakovano daje na manjšem testnem polju veliko boljše rezultate v smislu natančnosti, točnosti in razpršenosti. Približno 1000 evrov vredna naprava Apple iPad Pro 2020 se izkaže predvsem pri hitrosti in enostavnosti dela. Za naloge, ki se izvajajo na območjih velikosti manjšega testnega polja, daje naprava Apple, upoštevajoč ceno, zelo dobre rezultate.

Podobno je pri večjem testnem polju. Usmerjenost ravnin je sicer pri napravi Apple, kljub ceni, razmeroma točna, razlike pa se pojavijo pri položajni točnosti. Tukaj se opazi, da ima naprava Apple na večjih območjih težave z registracijo, ki vodijo do napačnega merila končnih rezultatov. Druga težava zajema večjih območji z napravo Apple je obseg. Naprava ni mogla izmeriti celotnega testnega polja, ki smo ga zato za potrebe preizkusov morali zmanjšati (slika 14).



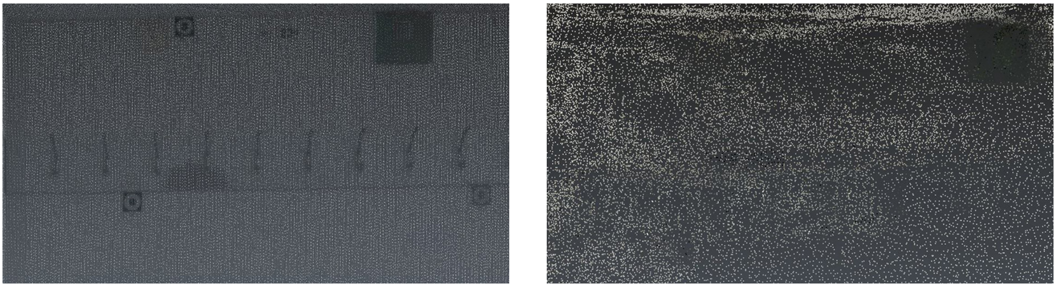
Slika 14: Oblaka točk večjega testnega polja, izmerjena z instrumentom Leica BLK360 (levo) in napravo Apple (desno).

Težave z registracijo naprave Apple se kažejo tudi kot dvojne stene na nekaterih objektih (slika 15).



Slika 15: Primerjava oblakov točk detajla večjega testnega polja, izmerjena z instrumentom Leica BLK360 (levo) in napravo Apple (desno).

Razlike se pojavijo tudi pri ločljivosti merskega sistema lidar, vgrajenega v napravi Apple, v primerjavi z napravo Leica BLK360. Prvi prostor opisuje z manj točkami, zaradi česar je oblak točk manj podroben (slika 16).



Slika 16: Primer odseka oblaka točk, zajetega z instrumentom Leica (levo) in z napravo Apple (desno).

Naprava Apple ima pri izmeri večjih območij težave, zato za potrebe 3D modeliranja notranjih prostorov ni primerna, glede na ceno pa še vedno daje zadovoljive rezultate.

5 ZAKLJUČEK

Rezultati praktičnih preizkusov kažejo, da lidar senzor v napravi Apple iPad Pro 2020 še ne dosega natančnosti manj kakor centimeter, ki je zaželena v nalogah 3D prikazov oziroma 3D modeliranja notranjih prostorov stavb. Kljub temu ga ne smemo označiti za neuporabnega. Lidar, vgrajen v pametne naprave, daje rezultate, ki so primerni za grobe vizualizacije prostorov, za virtualne sprehode, funkcije obogatene resničnosti in podobno. Pri zahtevnih geodetskih nalogah, kamor spadajo tudi 3D prikazi in 3D modeliranje notranjih prostorov, pa še vedno potrebujemo profesionalno geodetsko opremo.

Vgrajevanje senzorjev lidar v pametne naprave zaznamuje začetek novega obdobja zajema prostorskih podatkov, kjer bodo te lahko zajemali tudi laični uporabniki. Razvoj nizkocenovnih snemalnih sistemov lidar je še v povojih, zato lahko pričakujemo, da bo z razvojem laserskih diod in mikroprocesorjev kakovost rezultatov vse boljša. To bi lahko vodilo v pocenitev in večjo popularizacijo uporabe 3D skenerjev in s tem v podrobnejši ter kakovostnejši zajem prostorskih podatkov. Popularizacija in pocenitev naprav za lasersko skeniranje lahko pomenita tudi veliko količino podrobnih prosto dostopnih prostorskih podatkov, kar je za naloge, ki te podatke potrebujejo, sicer dobro, je pa težava kontrola kakovosti podatkov. Tu nastopimo geodeti, ki lahko s profesionalno opremo in inženirskim znanjem dosežemo višjo kakovost in zanjo tudi odgovarjamo.

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