Raziskava o natančnosti tehnologije LiDAR z uporabo aplikacije Scaniverse v pametnih telefonih iPhone

Investigation of the Accuracy of LiDAR Technology in iPhone Smartphones Using the Scaniverse Application

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IZVLEČEK

V članku so predstavljeni rezultati raziskave o natančnosti ustvarjanja tridimenzionalnih modelov z uporabo LiDAR senzorjev, vgrajenih v pametne telefone iPhone 12 Pro, 13 Pro Max in 15 Pro Max, ter mobilne aplikacije Scaniverse. Obdelani so bili različni objekti različnih oblik in velikosti – geodetski instrument v muzeju, kiparska kompozicija, učilnica in del zemeljske površine. Za vsak objekt so bili rezultati skeniranja primerjani z referenčnimi podatki, pridobljenimi s tradicionalnimi geodetskimi metodami, in opravljena je bila ocena natančnosti z izračunom srednje kvadratne napake. Rezultati so pokazali, da je za majhne in srednje velike objekte napaka skeniranja manjša od 1 % velikosti objekta, kar kaže na primernost pametnih telefonov iPhone za naloge digitalne vizualizacije, arhitekturno dokumentacijo in predhodne preglede. Pri skeniranju velikih homogenih površin pa se pojavljajo pomembna lokalna odstopanja, zlasti v odsotnosti geodetskega navezovanja. Raziskava potrjuje, da je natančnost modelov močno odvisna od velikosti objektov, teksture in odbojnih lastnosti površine.

ABSTRACT

This paper presents the results of a study on the accuracy of creating 3D models using LiDAR sensors integrated into the iPhone 12 Pro, 13 Pro Max, and 15 Pro Max smartphones, in conjunction with the Scaniverse mobile application. Various objects of different shapes and sizes were scanned, including a museum geodetic instrument, a sculptural composition, a classroom, and a section of the earth's surface. For each object, the scanning results were compared with reference data obtained through traditional geodetic methods, and accuracy was evaluated by calculating the root mean square error. The results showed that for small- and medium-sized objects, scanning errors were less than 1% of the object's dimensions, indicating the suitability of iPhone smartphones for tasks such as digital visualization, architectural documentation, and preliminary surveying. However, significant local deviations were observed when scanning large homogeneous surfaces, particularly in the absence of geodetic control. The study confirms that the accuracy of models largely depends on the size of the objects, surface texture, and reflective properties.

KLJUČNE BESEDE

LiDAR, iPhone 12 Pro, iPhone 13 Pro Max, iPhone 15 Pro Max, ocena natančnosti, tridimenzionalni model, oblak točk, terestrično lasersko skeniranje

KEY WORDS

LiDAR, iPhone 12 Pro, iPhone 13 Pro Max, iPhone 15 Pro Max, accuracy assessment, 3D model, point cloud, terrestrial laser scanning

1 Introduction

In the current conditions of rapid digital technology development, increasing attention is being paid to the use of mobile devices for geospatial measurements and 3D modeling. One such innovative solution is the integrated LiDAR sensors in iPhone smartphones, which enable real-time laser scanning without additional equipment.

This technology is widely applied in fields such as documentation of cultural and architectural heritage objects, scanning of sculptures and architectural details, creation of digital copies of interior spaces, asset inventory, and preparation of visual models for virtual and augmented reality.

Despite the growing popularity of this technology, there is a need for a detailed study of its accuracy and reliability under various conditions. This is due to the fact that results obtained using mobile LiDAR sensors can significantly depend on factors such as lighting, surface reflectivity, the size and shape of the object, as well as the distance to it. Moreover, the accuracy of the resulting models may vary depending on how the device is moved, the stability of the user's hand, and the software used for scan processing. Therefore, it is relevant to study the capabilities and limitations of this technology, particularly by comparing it with traditional 3D scanning methods and geodetic measurements.

Accordingly, it is advisable to conduct experiments in various scenarios, such as scanning building interiors, cultural heritage objects (e.g., sculptures), architectural façades with varying complexity, and small objects with fine geometric details. Comparing the results of such scans with data obtained through traditional geodetic methods or professional 3D scanners enables an objective assessment of the accuracy level of mobile LiDAR under real-world conditions.

The goal of this work is to assess the geometric accuracy of LiDAR scanning using iPhone smartphones for objects of various sizes by comparing the obtained results with data from traditional geodetic methods.

1.1 Overview of the literature

The LiDAR sensor in the iPhone 12–15 Pro models is located in the lower right corner of the camera cluster, as shown in Figure 1. The sensor uses time-of-flight (ToF) principles and consists of a source of photons, or emitter, and a receiver. The laser is emitted from a Vertical Cavity Surface Emitting Laser (VCSEL) at a near infrared spectrum. The direct time of flight (dTOF) of the pulses emitted by the VCSEL is measured with a Single Photon Avalanche Photodiode (SPAD). 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. Increases in power density of VCSELs in combination with SPADs makes flash-LiDAR solutions feasible for consumer-grade devices like the iPad and iPhone (Tondo et al., 2023; Luetzenburg et al., 2021; Vipavec & Kregar, 2024).

Apple does not publish detailed technical specifications for the sensors in different iPhone models or information about their differences; thus, it can be inferred that the sensors are identical. Known improvements relate to data processing (software) and integration with other sensors (Apple, n.d.).

Currently, there are many publications concerning the potential use of iPhone LiDAR for geodetic tasks and the study of the accuracy of the resulting models. However, the results vary depending on object size, distance, and the scanning software used.

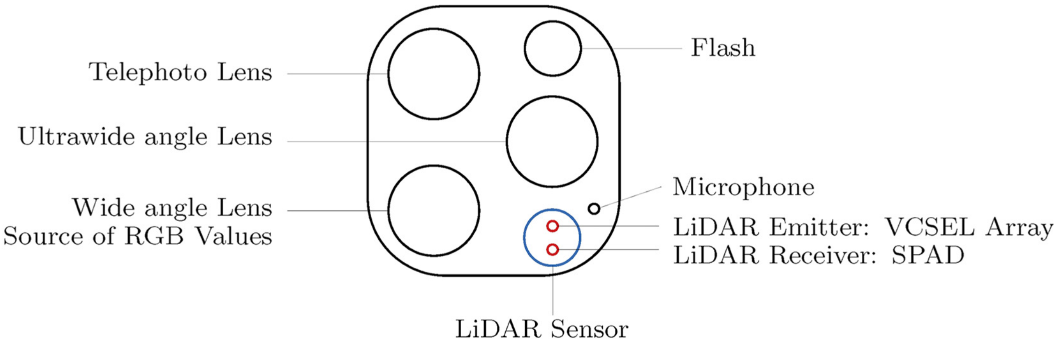

Figure 1: Arrangement of the iPhone 13 Pro camera cluster, including the location of the LiDAR emitter and receiver (Source: Tondo et al., 2023)

In the article "Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences" (Luetzenburg et al., 2021), the authors investigated the accuracy and suitability of the iPhone 12 Pro LiDAR sensor for creating 3D models of natural objects. They conducted experimental scanning of a coastal cliff in Denmark, comparing the results with Structure from Motion Multi-View Stereo (SfM MVS) point clouds. The results showed that the iPhone 12 Pro LiDAR sensor can create high-quality 3D models of small objects (with sides over 10 cm) with an absolute accuracy of ±1 cm. For larger objects, such as cliffs measuring up to 130 × 15 × 10 m, the absolute accuracy was about ±10 cm.

In the study "Evaluating the Accuracy of iPhone Lidar Sensor for Building Façades Conservation" (Abbas & Abed, 2024), the positional accuracy of the LiDAR sensor in the iPhone 12 Pro Max was analyzed when scanning building façades. The Sitescape app was used for scanning. The study was conducted on a building façade with control points measured by a total station. The iPhone sensor demonstrated millimeter-level accuracy.

In "The iPad Pro Built-in Lidar Sensor: 3D Rapid Mapping Tests and Quality Assessment" (Spreafico et al., 2021), the accuracy of the iPad Pro sensor was evaluated while scanning façades and architectural elements. The RMSE of the resulting point clouds was estimated at 2 cm.

In the article "Quality Assessment of LiDAR in Apple Digital Devices" (Vipavec & Kregar, 2024), the accuracy of laser scanning using the built-in LiDAR sensor in the Apple iPad Pro was studied. The authors performed experiments on two test objects – wooden boxes (approximately 1 m in size) and a room (about 10 m in size). For the smaller object, the RMSE was 15 mm. However, for the room, some deviations reached 0.478 m. The authors concluded that the LiDAR system in Apple devices cannot provide relative positional accuracy better than 10 cm.

In "The Accuracy Evaluation of Point Cloud Data Generated with iPhone 15 Pro Next Gen LiDAR Sensor" (Kuçak, 2023), the iPhone 15 Pro LiDAR and the SiteSCAPE and Scaniverse mobile apps were tested. When measuring line lengths up to 1 meter, the RMSE was 3 mm.

In the study "Apple LiDAR Sensor for 3D Surveying: Tests and Results in the Cultural Heritage Domain" (Teppati Losè et al., 2022), the accuracy of scanning with the iPad Pro and iPhone 12 Pro using different apps (SiteScape, EveryPoint, and 3D Scanner App) was analyzed both outdoors and indoors under various lighting conditions and on different materials. The analysis showed that the same LiDAR sensor is used in both iPad Pro and iPhone 12 Pro. However, each app produced different results, highlighting the critical role of software when using the same hardware. Tests conducted under dim and bright sunlight conditions and on different materials showed that lighting and material had minimal impact on the sensor. These tests, based on three real-world scenarios, confirmed that the sensor can be effectively used for scanning small and medium-sized objects (e.g., statues, museum pieces, small rooms, or parts of buildings, decorative architectural elements, etc.) with centimeter-level accuracy and high detail.

The important role of data collection software is also confirmed by the study "Assessing the Effectiveness of LiDAR-Based Apps on Apple Devices to Survey Indoor and Outdoor Medium-Sized Areas" (Treccani et al., 2024), which evaluated the accuracy of five different apps (3D Scanner App, Dot3D, Polycam, RTAB-Map, Scaniverse). Their effectiveness was tested on two examples – an indoor corridor with rooms and a section of a street. Each app processed the data differently and showed very different results. Typically, errors ranged from a few centimeters to several tens of centimeters, including local deviations.

In the article "Smartphone-based LiDAR for generating Digital Outcrop Models (DOMs) with field validation" (Furlan & Piazentim, 2025) evaluated the accuracy of creating Digital Outcrop Models (DOM) using LiDAR integrated into iPhone smartphones. The authors compared different scanning parameters, including the distance to the scanned surface, and found that the optimal range of 2.5 m provides the best balance between accuracy and efficiency. The following applications were tested: DOT3D, KIRI Engine, LiDAR Scanner, Luma 3D, Modelar, PolyCam, Scaniverse, SiteScape, and 3D Scanner App. Among the free applications, Scaniverse demonstrated the best results, while CloudCompare was recommended for detailed analysis.

2 Methods

2.1 Research conditions

In this study, the accuracy of scanning objects of various sizes using iPhone smartphones was assessed. Specifically:

- a museum geodetic instrument (theodolite "M. Tauber, K. Tsvetkov & Co."), approximately 0.2 by 0.3 meters in size;
- the sculptural composition of the fountain "Dragon Slayer", measuring 3 by 4 meters;
- a lecture hall, measuring 6 by 13 meters;
- a section of the Earth's surface with asphalt pavement, measuring 9 by 15 meters.

The objects were scanned using iPhone 12 Pro, 13 Pro Max, and 15 Pro Max smartphones. Considering the results of the study by Furlan and Piazentim (2025), in which the Scaniverse (Scaniverse, n.d.) application demonstrated the highest scanning accuracy among the tested programs, this application was selected for the implementation of the experimental part of our research.

During all experiments, scanning was performed under stable indoor or daylight conditions without direct sunlight glare on the object. Scanning distance was kept within the optimal operating range of the iPhone LiDAR sensor — between 0.5 and 4 m, depending on the object's size. Smartphone stability was ensured by slow and uniform movement around the object.

2.2 Accuracy assessment

Accuracy was assessed by comparing deviations in coordinates or distances from the scanned model to reference values obtained via traditional geodetic methods. The values obtained using classical methods (electronic total station, terrestrial laser scanning, and geometric leveling) were taken as reference values. Based on the calculated deviations, the root mean square error (RMSE) of coordinate (distance) *m* determination was calculated using the following formula (Voitenko, 2003):

$$m = \sqrt{\frac{[V_i V_i]}{n-1}} \quad (1)$$

where Vi – is the difference between the dimensions determined from the model and those accepted as reference; n – is the number of control points.

CloudCompare software (CloudCompare, n.d.) was used to work with the scanned 3D models.

3 Results

3.1 Scanning of the museum geodetic instrument

The study "Comparison of the accuracy of 3D models created using the LiDAR system of the iPhone 12 Pro and iPhone 13 Pro Max" (Yanchuk et al., 2024a) presents a comparative analysis of the accuracy of 3D models created using the LiDAR systems of iPhone 12 Pro and iPhone 13 Pro Max smartphones. For this purpose, a museum geodetic instrument — the theodolite "M. Tauber, K. Tsvetkov & Co." — approximately 0.2 by 0.3 meters in size, was scanned.

The scanning was performed using the Scaniverse application with the "Small Object" setting, a distance of 0.8 m from the object, and a high-detail mode for the final model. As a result, two 3D models of the same object were obtained (Figure 2).

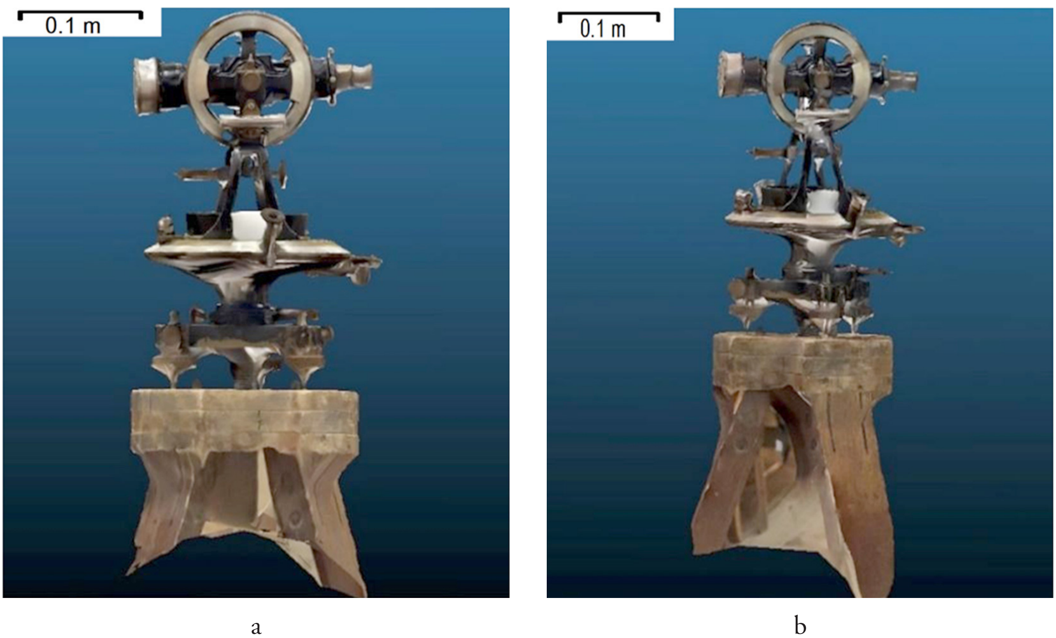

Figure 2: 3D models created using LiDAR: a) with iPhone 12 Pro; b) with iPhone 13 Pro Max (Source: Yanchuk et al., 2024a)

The resulting models exhibit similar quality in object reproduction. The main structural elements were scanned quite accurately. However, both models exhibit certain distortions, blurring, and deformation of small details.

To assess accuracy, the dimensions of 20 distinct contours of the instrument were measured with a ruler and accepted as reference. In CloudCompare, the same contours were measured on the 3D models obtained using the LiDAR sensors of the iPhone 12 Pro and iPhone 13 Pro Max. The deviations of the values measured from the 3D models from the reference values were calculated, and the corresponding root mean square errors (RMSE) were computed using formula (1).

The RMSE of the overall dimensions of the main structural elements, measured from the model obtained with the iPhone 12 Pro LiDAR, was 1.8 mm. The RMSE of the dimensions measured from the model obtained with the iPhone 13 Pro Max LiDAR was 1.7 mm.

The slight differences in RMSE are attributed to random errors and indicate the use of the same LiDAR sensor in different iPhone models. Given the small size of the theodolite, the resulting errors represent about 1% of the object's size.

3.2 Scanning of the "Dragon Slayer" fountain sculpture composition

The article “Investigation of the accuracy of a 3D model of a monument created using LiDAR iPhone 12 Pro” (Yanchuk et al., 2024b) examines the accuracy of creating a 3D model of a sculpture using the LiDAR system of the iPhone 12 Pro. The object chosen for scanning was the "Dragon Slayer" monument, measuring 3 by 4 meters, which is part of a fountain composition in Taras Shevchenko Park of Culture and Recreation in Rivne, Ukraine. To investigate the accuracy of the iPhone 12 Pro LiDAR, the point cloud obtained from the iPhone was compared to a reference model.

The reference model was acquired using a ground-based Faro Laser Scanner Focus 3D within a local coordinate system. To enable stitching of individual scans, a geodetic reference network was established, with 3D coordinates of characteristic points on different sides of the monument measured. A total of 10 control points were used. Terrestrial laser scanning was performed from three stations, each covering at least 3–4 control points. After processing the scan data, a point cloud in e57 format was obtained (file size: 1.92 GB, number of points: 137 484 259).

Scanning was also performed using the iPhone 12 Pro. The smartphone was mounted on a selfie stick to access the upper parts of the sculpture. The scanning was carried out in Scaniverse software in “Mesh” mode, with the object size set to Large Object/Area, LiDAR range of 5 m, and processing mode set to area. The result was a point cloud in LAS format (file size: 10 MB, number of points: 395 090). Scanning took 5 minutes and no reference points were used. Figure 3 shows a comparison of the sculpture models obtained with the ground-based laser scanner and the iPhone.

In CloudCompare, the two point clouds were aligned using four common points on the sculpture (as the models were in different coordinate systems). According to the software's statistical calculations, the alignment accuracy at this stage was 0.025 m. The differences in geometric positions of the points in the compared point clouds were calculated using CloudCompare (Cloud-to-Cloud Distance, n.d.). The results are presented in Figure 4, with numerical deviation characteristics shown in Figure 5. The vast majority of deviations fall within 0.03 m, with a maximum deviation of 0.27 m. The largest deviations occur in hard-to-reach areas. For the main sculpture body, deviations are up to 5 cm.

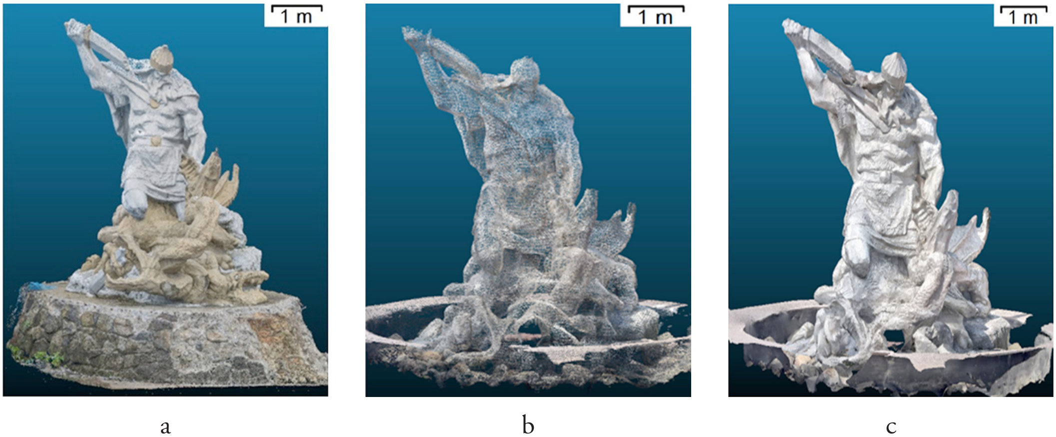

Figure 3: Comparison of sculpture models: a) obtained with a ground-based laser scanner; b) point cloud (iPhone 12 Pro); c) textured model (iPhone 12 Pro) (Source: Yanchuk et al., 2024b)

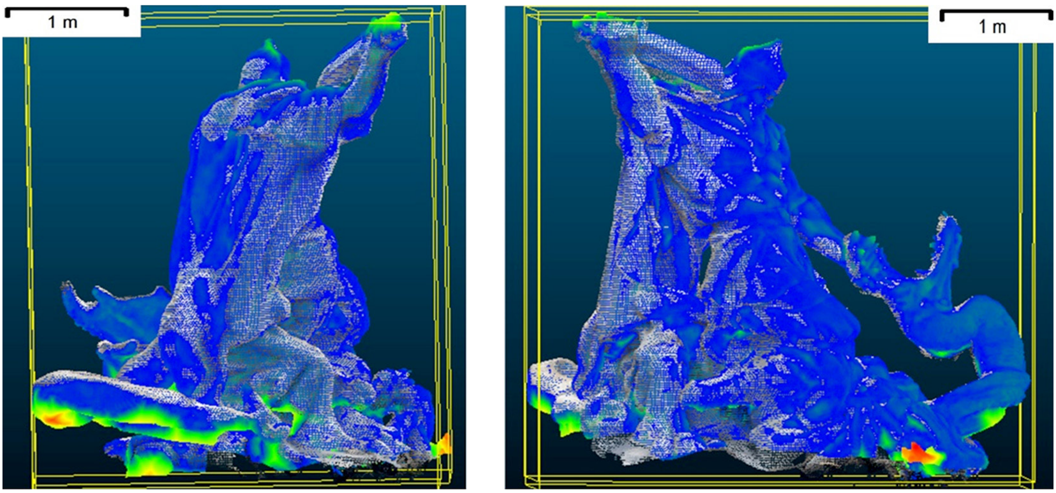

Figure 4: Difference between two point clouds (Source: Yanchuk et al., 2024b)

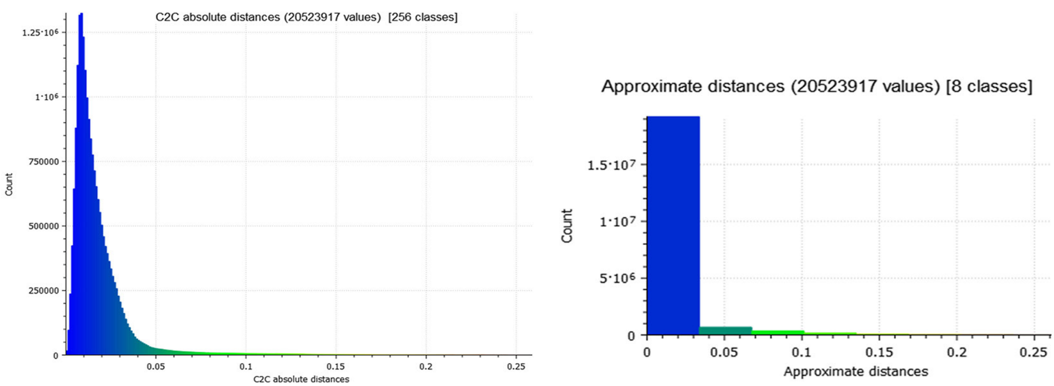

Figure 5: Numerical characteristics of differences between point clouds (Source: Yanchuk et al., 2024b)

Given the sculpture's dimensions of 3 by 4 meters, the obtained RMSE values of 0.03–0.05 m amount to approximately 1% of the object's size.

3.3 Scanning of a classroom

In the article "Accuracy assessment of a 3D model obtained using the LiDAR sensor of the iPhone 13 Pro Max" (Yanchuk et al., 2025), a classroom measuring 6 by 13 meters was scanned using the LiDAR sensor of the iPhone 13 Pro Max smartphone. Twelve markers with known coordinates (determined using traditional geodetic methods) were placed on the walls of the room. Comparison was conducted between the line lengths and coordinates derived from the LiDAR-scanned model and the precise data measured using a Leica TCR 405 Ultra electronic total station, as well as from a model created photogrammetrically using images captured with a Sony Cyber-shot DSC-RX100 camera.

Scanning with a smartphone was performed using the Scaniverse application (Scaniverse, n.d.) with parameters recommended for indoor scanning: object size – Large Object/Area, processing mode – area. The scanning was done handheld, moving around the classroom so that the distance to the walls was 2–4 meters. In other words, no additional tools for spatial stabilization of the smartphone (such as a tripod, gimbal) were used. The scanned model is shown in Figure 6.

The point cloud contains a total of 833 492 points. Overall, the quality of the model can be considered satisfactory. Most elements have clear geometry. However, some fragments contain distortions or missing sections, and window glass is displayed incorrectly. Additionally, the floor and ceiling are absent in this model, and the instrument placement columns are only partially represented, since capturing those elements was not the objective — the control markers were placed only on the walls. The control markers are clearly visible in the model, allowing their coordinates to be unambiguously identified.

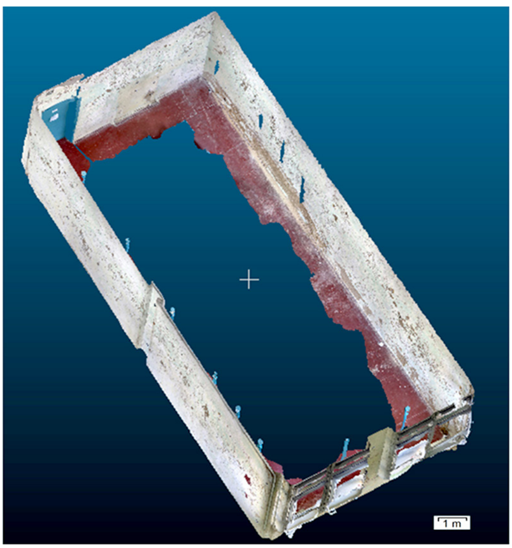

Figure 6: Overview of the model scanned using LiDAR on iPhone 13 Pro Max (Source: Yanchuk et al., 2025)

To assess the accuracy, the LiDAR model was elastically transformed into the coordinate system of the room using the coordinates of 10 points previously determined with a total station. This transformation allows for comparing the coordinates of control targets from the georeferenced LiDAR model with those obtained using the total station and with coordinates derived from a photogrammetric model. The root mean square error (RMSE) of deviations along individual axes ranges from 0.021 to 0.029 m. The spatial RMSE in both cases (relative to the total station measurements and the photogrammetric model) is 0.045 m. In addition, distances between all combinations of the targets (66 lines) were calculated based on the coordinates determined by all three methods, and the RMSE of the distance measurements was computed. The RMSE of distances is 0.042 m when compared to total station measurements, and 0.043 m when compared to the values obtained from the photogrammetric model.

To evaluate the accuracy without applying any transformation, 66 distances between 12 control targets in all possible combinations were measured from the obtained point cloud using the CloudCompare software. The root mean square error (RMSE) of the model was calculated using Equation (1), based on the deviations of distances between control targets in the point cloud from those measured with a total station. In this case, the RMSE of distance determination is 0.042 m.

Thus, as shown by the results of the study, the accuracy of the model does not depend on whether a transformation to another object coordinate system is applied. However, when working with a non-transformed model, it is advisable to use a reference measurement as a control for the obtained results.

In the analyzed cases, the accuracy of the LiDAR model was found to be within 0.04–0.05 m, which in this context is less than 1% of the linear dimensions of the room.

3.4 Scanning of an asphalt-paved ground surface area

In addition to the previously described studies, an asphalt-paved ground surface area measuring 9 by 15 meters was scanned using the LiDAR sensor of the iPhone 15 Pro Max. A grid of 1-meter square cells was marked on the test area (Figure 7).

Figure 7: Marked square grid on the asphalt-covered area

To obtain reference elevation values at the grid vertices, differential leveling was carried out along the grid using a Stonex D1 digital level. The total elevation difference across the area was 0.818 meters. The leveling log and the grid vertex numbering scheme are presented in Figure 8.

Subsequently, the surface was scanned using the iPhone 15 Pro Max and the Scaniverse application (Scaniverse, n.d.). The chosen parameters were: object size – Large Object/Area, processing mode – area.

Scanning the entire area in a single pass produced unsatisfactory results. Visually, there were noticeable gaps and significant surface irregularities, particularly at the joints between different scan fragments (Figure 9). This can be attributed to the uniform texture of the scanned surface.

i \ *j*	1	2	3	4	5	6	7	8	9	10
16	0.7860	0.8036	0.8858	0.8760	0.8770	0.8288	0.8248	0.8434	0.8624	0.8700
15	0.8774	0.8826	0.8828	0.9168	0.9190	0.8950	0.8892	0.8968	0.9260	0.9258
14	0.9210	0.9262	0.9434	0.9744	0.9780	0.9392	0.9286	0.9344	0.9468	0.9602
13	0.9654	0.9804	0.9858	1.0330	1.0306	0.9732	0.9824	0.9800	0.9888	0.9898
12	1.0184	1.0254	1.0286	1.0738	1.0688	1.0330	1.0324	1.0266	1.0280	1.0076
11	1.0772	1.0758	1.0724	1.1240	1.1118	1.0814	1.0832	1.0664	1.0652	1.0534
10	1.1240	1.1328	1.1238	1.1506	1.1554	1.1340	1.1286	1.1166	1.1126	1.0926
9	1.1820	1.1806	1.1864	1.1772	1.1852	1.1722	1.1596	1.1606	1.1541	1.1318
8	1.2330	1.2380	1.2358	1.2442	1.2300	1.2184	1.2066	1.1982	1.1910	1.1692
7	1.2874	1.2868	1.2894	1.2968	1.2864	1.2586	1.2464	1.2292	1.2292	1.2142
6	1.3410	1.3312	1.3350	1.3386	1.3184	1.2994	1.2906	1.2768	1.2365	1.2654
5	1.4028	1.3854	1.3878	1.3812	1.3756	1.3644	1.3436	1.3366	1.3560	1.2964
4	1.4496	1.4524	1.4516	1.4518	1.4386	1.4206	1.4068	1.3912	1.3786	1.2838
3	1.5024	1.5016	1.5072	1.5074	1.4826	1.4666	1.4450	1.4280	1.4057	1.3622
2	1.5368	1.5514	1.5656	1.5560	1.5202	1.5066	1.4766	1.4482	1.4262	1.3710
1	1.5904	1.5704	1.6044	1.5988	1.5630	1.5256	1.4970	1.4534	1.4258	1.3884

Figure 8: Leveling log for the squares and vertex numbering scheme

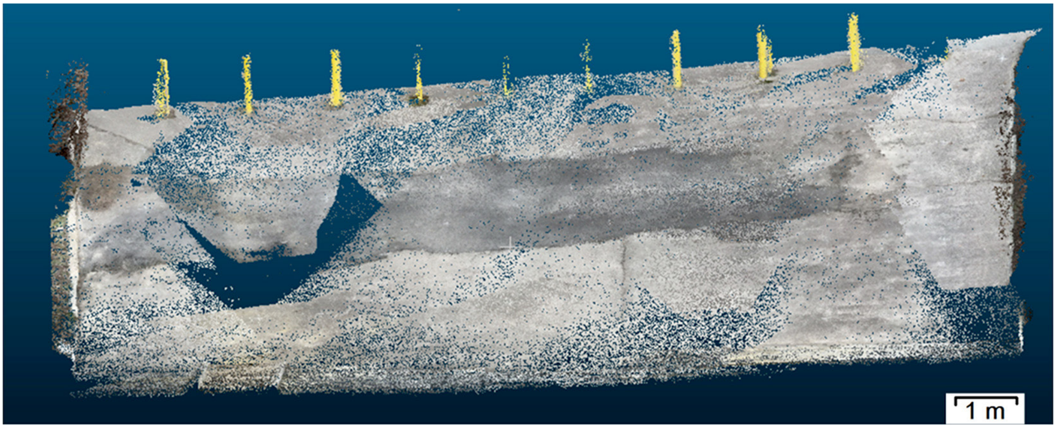

Figure 9: Unsatisfactory result of scanning the entire area in a single pass

It was decided to perform scanning in separate passes, each 3 meters wide. The scanning results of each pass were elastically transformed using 5 points into a local coordinate system in order to align the point cloud with the elevation system chosen at the initial stage. The result is shown in Figure 10.

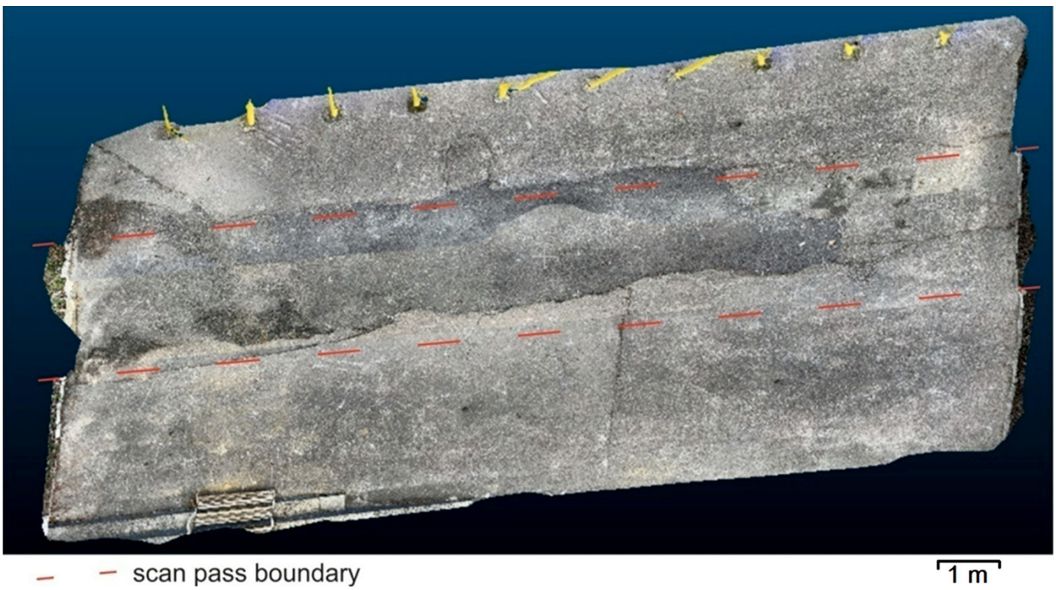

Figure 10: Result of scanning the area using three separate passes

At the next stage, the elevations of the grid vertices determined from the LiDAR model were compared with those obtained from geometric leveling, using CloudCompare. The comparison results are presented in Tables 1–3. Accuracy assessment was carried out based on deviation results using formula (1).

Table 1: Comparison of elevations determined from the LiDAR model with those obtained from geometric leveling (Pass 1)

A row of squares, i	Heights determined by LiDAR model, m				Heights determined by geometric leveling, m				Deviation LiDAR - level, m			
	Column of squares, j				Column of squares, j				Column of squares, j			
	1	2	3	4	1	2	3	4	1	2	3	4
16	0.766	0.744	0.717	0.709	0.804	0.787	0.705	0.714	-0.038	-0.043	0.012	-0.005
15	0.757	0.739	0.686	0.494	0.713	0.708	0.708	0.674	0.044	0.031	-0.022	-0.180
14	0.721	0.692	0.657	0.661	0.669	0.664	0.647	0.616	0.052	0.028	0.010	0.045
13	0.671	0.646	0.611	0.614	0.625	0.610	0.605	0.557	0.046	0.036	0.006	0.057
12	0.634	0.599	0.550	0.587	0.572	0.565	0.562	0.517	0.062	0.034	-0.012	0.070
11	0.597	0.553	0.487	0.523	0.513	0.515	0.518	0.466	0.084	0.038	-0.031	0.057
10	0.545	0.509	0.440	0.470	0.466	0.458	0.467	0.440	0.079	0.051	-0.027	0.030
9	0.503	0.461	0.402	0.362	0.408	0.410	0.404	0.413	0.095	0.051	-0.002	-0.051
8	0.443	0.399	0.361	0.283	0.357	0.352	0.355	0.346	0.086	0.047	0.006	-0.063
7	0.388	0.344	0.289	0.232	0.303	0.304	0.301	0.294	0.085	0.040	-0.012	-0.062
6	0.329	0.286	0.228	0.159	0.249	0.259	0.255	0.252	0.080	0.027	-0.027	-0.093
5	0.269	0.217	0.165	0.086	0.188	0.205	0.203	0.209	0.081	0.012	-0.038	-0.123
4	0.217	0.176	0.118	0.048	0.141	0.138	0.139	0.139	0.076	0.038	-0.021	-0.091
3	0.159	0.102	0.050	-0.024	0.088	0.089	0.083	0.083	0.071	0.013	-0.033	-0.107
2	0.070	0.035	-0.012	-0.093	0.054	0.039	0.025	0.034	0.016	-0.004	-0.037	-0.127
1	0.044	0.078	0.038	0.030	0.000	0.020	-0.014	-0.008	0.044	0.058	0.052	0.038
								RMSE		**0.060**		

Table 2: Comparison of elevations determined from the LiDAR model with those obtained from geometric leveling (Pass 2)

A row of squares, i	Heights determined by LiDAR model, m				Heights determined by geometric leveling, m				Deviation LiDAR - level, m			
	Column of squares, j				Column of squares, j				Column of squares, j			
	4	5	6	7	4	5	6	7	4	5	6	7
16	0.697	0.743	0.734	0.762	0.714	0.713	0.762	0.766	-0.017	0.030	-0.028	-0.004
15	0.669	0.710	0.734	0.765	0.674	0.671	0.695	0.701	-0.005	0.039	0.039	0.064
14	0.654	0.684	0.700	0.730	0.616	0.612	0.651	0.662	0.038	0.072	0.049	0.068
13	0.607	0.660	0.651	0.691	0.557	0.560	0.617	0.608	0.050	0.100	0.034	0.083
12	0.548	0.600	0.616	0.657	0.517	0.522	0.557	0.558	0.031	0.078	0.059	0.099
11	0.502	0.553	0.575	0.617	0.466	0.479	0.509	0.507	0.036	0.074	0.066	0.110
10	0.449	0.511	0.534	0.570	0.440	0.435	0.456	0.462	0.009	0.076	0.078	0.108
9	0.382	0.439	0.494	0.508	0.413	0.405	0.418	0.431	-0.031	0.034	0.076	0.077
8	0.359	0.393	0.439	0.475	0.346	0.360	0.372	0.384	0.013	0.033	0.067	0.091
7	0.309	0.351	0.381	0.393	0.294	0.304	0.332	0.344	0.015	0.047	0.049	0.049
6	0.247	0.285	0.311	0.342	0.252	0.272	0.291	0.300	-0.005	0.013	0.020	0.042
5	0.188	0.222	0.286	0.280	0.209	0.215	0.226	0.247	-0.021	0.007	0.060	0.033
4	0.146	0.187	0.215	0.234	0.139	0.152	0.170	0.184	0.007	0.035	0.045	0.050
3	0.095	0.115	0.151	0.156	0.083	0.108	0.124	0.145	0.012	0.007	0.027	0.011
2	0.016	0.048	0.079	0.084	0.034	0.070	0.084	0.114	-0.018	-0.023	-0.005	-0.030
1	0.021	0.004	0.011	0.031	-0.008	0.027	0.065	0.093	0.029	-0.023	-0.054	-0.062
								RMSE		**0.052**		

Table 3: Comparison of elevations determined from the LiDAR model with those obtained from geometric leveling (Pass 3)

A row of squares, i	Heights determined by LiDAR model, m				Heights determined by geometric leveling, m				Deviation LiDAR - level, m			
	Column of squares, j				Column of squares, j				Column of squares, j			
	7	8	9	10	7	8	9	10	7	8	9	10
16	0.795	0.762	0.742	0.734	0.766	0.747	0.728	0.720	0.029	0.015	0.014	0.014
15	0.712	0.695	0.658	0.659	0.701	0.694	0.664	0.665	0.011	0.001	-0.006	-0.006
14	0.646	0.635	0.627	0.627	0.662	0.656	0.644	0.630	-0.016	-0.021	-0.017	-0.003
13	0.584	0.577	0.586	0.608	0.608	0.610	0.602	0.601	-0.024	-0.033	-0.016	0.007
12	0.52	0.526	0.521	0.578	0.558	0.564	0.562	0.583	-0.038	-0.038	-0.041	-0.005
11	0.46	0.469	0.483	0.513	0.507	0.524	0.525	0.537	-0.047	-0.055	-0.042	-0.024
10	0.4	0.418	0.428	0.466	0.462	0.474	0.478	0.498	-0.062	-0.056	-0.050	-0.032
9	0.372	0.371	0.387	0.426	0.431	0.430	0.436	0.459	-0.059	-0.059	-0.049	-0.033
8	0.329	0.335	0.356	0.405	0.384	0.392	0.399	0.421	-0.055	-0.057	-0.043	-0.016
7	0.292	0.313	0.311	0.359	0.344	0.361	0.361	0.376	-0.052	-0.048	-0.050	-0.017
6	0.254	0.267	0.275	0.313	0.300	0.314	0.354	0.325	-0.046	-0.047	-0.079	-0.012
5	0.214	0.224	0.206	0.294	0.247	0.254	0.234	0.294	-0.033	-0.030	-0.028	0.000
4	0.159	0.184	0.187	0.254	0.184	0.199	0.212	0.307	-0.025	-0.015	-0.025	-0.053
3	0.137	0.146	0.186	0.25	0.145	0.162	0.185	0.228	-0.008	-0.016	0.001	0.022
2	0.116	0.153	0.181	0.263	0.114	0.142	0.164	0.219	0.002	0.011	0.017	0.044
1	0.024	0.035	0.084	0.123	0.093	0.137	0.165	0.202	-0.069	-0.102	-0.081	-0.079
								RMSE		**0.040**		

The obtained RMS errors (RMSE) for individual scanning passes range between 0.040 and 0.060 m. The overall RMSE, calculated from all measurements, is 0.052 m. However, individual deviations vary from -0.180 to +0.110 m, which requires further investigation to identify their causes.

Thus, for an area of 9 by 15 meters, an RMSE of approximately 0.05 m for height determination was obtained. However, considering that the total height variation within this area is 0.818 m, this error represents about 6% of the height range. Even this level of accuracy was achieved under specific conditions:

- it is recommended to divide the scanned area into individual strips and limit scanning to one pass per strip width;
- scan data of homogeneous surfaces with uniform relief should not be considered reliable without georeferencing. Therefore, it is recommended to use at least five control points for alignment;
- for homogeneous surfaces (such as asphalt), low-quality scan stitching by the smartphone's automatic algorithm was observed.

4 Conclusion

A detailed analysis of the results of scanning various objects using iPhones equipped with LiDAR technology in Scaniverse application has led to the following conclusions:

The root mean square error of the overall dimensions of the main structural elements of the theodolite model is nearly the same for the iPhone 12 Pro and iPhone 13 Pro Max (1.7 mm and 1.8 mm, respectively). This indicates that both smartphones use the same type of LiDAR sensor and that hardware differences have minimal impact on accuracy. In both cases, the main structural elements were scanned with relatively high quality; however, both models show some distortions, blurring, and deformation of small details.

A clear relationship between RMSE and object size is observed: RMSE of 0.017–0.018 m for the theodolite (size: 0.2 × 0.3 m); RMSE of 0.03–0.05 m for the sculpture (size: 3 × 4 m); RMSE of 0.04–0.05 m for the classroom (size: 6 × 13 m). In all these cases, the error is less than 1% of the object's size, which is acceptable for many digital visualization tasks. Therefore, it is recommended to assess scanning accuracy in relative terms.

Significantly poorer results were obtained when determining elevations from the model of the asphalt-paved area. In the case of scanning an asphalt-covered site measuring 9 by 15 meters, the error in elevation measurements reached 6%. Thus, when scanning, it is important to consider the geometry, texture, and reflectivity of the surface. A detailed analysis of these factors requires further research.

Difficulties arise when scanning large and homogeneous surfaces. To ensure the accuracy of scanning large areas, it is advisable to divide them into separate strips and subsequently transform the object using control points.

The established accuracy of models constructed using the iPhone's LiDAR sensor allows this device to be effectively used for creating 3D models of small objects. For example, it can be applied in the digitization of museum exhibits, scanning of architectural elements, and similar tasks.

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