Evaluation of the LiDAR in the Apple iPhone 13 Pro for use in Inventory Works

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Key words: Apple iPhone 13 Pro, inventory, terrestrial laser scanning

SUMMARY

Modern-day surveying, in contrast to traditional labor-intensive methods, is based mainly on linear and angular measuring techniques, laser rangefinders, terrestrial laser scanners (TLS) and handheld laser scanners, which make it possible to reduce the measurement team to one person, to increase the accuracy of the work performed by obtaining a quasi-continuous model of the object, and facilitate measurement directly on the object. Unfortunately, the new methods also require highly expensive measuring equipment and software, as well as the personnel to process point clouds. One alternative that is a compromise in terms of price and accuracy are photogrammetric techniques that use digital images to build a model in the form of a point cloud. However, they also come with a certain disadvantage – they require complex training of staff on how to correctly take images.

In 2020, Apple Inc. produced the first phone with an innovative built-in Light Detection And Ranging (LiDAR)-based depth sensors and enhanced augmented reality (AR) application programming interface (API). The device constitutes a relatively inexpensive competitor to current hardware solutions used in surveying requiring moderate accuracy. It does not perform surface scanning in the sense of TLS devices, but it can obtain a color point cloud at a scale of 1:1. In this paper, we test the basic capabilities of the iPhone 13 Pro LiDAR in performing typical tasks in the field of building inventory. An office room and sample architectural details such as arches in lintels were scanned and the obtained results were compared with measurements made using a precise terrestrial laser scanner. We present the advantages and disadvantages of the tested device, and also show the capability of obtaining the measurement accuracy of 1 cm required in building inventory.

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1. INTRODUCTION

An architectural (as-built) or construction inventory involves creating drawing documentation of an existing facility as the basis for commencing further design work (Rosolski et al., 2021). Thanks to the high quality of modern equipment and devices, inventories can be carried out very efficiently and quickly. Currently, angular-linear measurement techniques, laser rangefinders, terrestrial laser scanners (TLS), handheld laser scanners and terrestrial photogrammetry are used in inventory measurements. The use of terrestrial laser scanning for inventories has facilitated a reduction in the number of people in the measurement team to just one, has increased the accuracy of the work performed by obtaining a quasi-continuous model of the object, and has accelerated the direct measurement of the object. Such measurements are non-invasive, safe and extremely precise. Depending on the scope of the inventory, portions of the physical object or all elements of the object can be selected. Typically, an inventory would produce 2D plan drawings, vector graphics, or digital three-dimensional models. As a way to optimize inventory work, it has been suggested to introduce a four-stage process aimed at creating the most accurate documentation possible, corresponding to the needs of the designer. The first stage can be a drawing inventory, the second – a construction inventory, the third – a laser inventory, and the fourth – a 3D scan with complex geometric detail (Rosolski et al., 2021).

A drawing inventory would initiate measurements and estimate the overall dimensions of the analyzed object. Because of the low equipment requirements and the relatively low cost, the data collected in this way would provide an excellent estimate to determine the initial cost of the planned work and the time to complete it. The final result and scope of the work would depend on the needs and intentions of the client and may include: a description of the building, list of surfaces, projections of the roof, floors and elevation, cross-sections, drawings of electrical and sanitary installations (schemes, projections, expansions, etc.). Using laser scanning inventory measurements facilitates creating models of buildings in BIM (building information modeling/management) technology by reconstructing their structure with full design information in an interactive 3D environment (Krysiak, 2018). BIM technology holds enormous potential for improving the level of automation in the Architecture, Engineering, and Construction (AEC) sector and is increasingly becoming a standard in many countries (Skrzypczak et al., 2022, Piaia et al., 2021). BIM models facilitate creating precise documentation of an object, as well as conducting structural and strength analyses, efficient handling of the technical parameters of the object, as well as optimal planning of intended works. As the needs for carrying out such an inventory are wide, the accuracy should be adjusted accordingly.

Angular-linear measurement techniques, laser rangefinders, terrestrial laser scanners (TLS) and handheld laser scanners are commonly used for investigative measurements. The use of terrestrial laser scanners has increased the accuracy and quality of the acquired data, as well as increased the cost of the work performed, resulting mainly from the price of the measuring equipment, the software used and the cost of personnel to process the point clouds. An alternative that finds a compromise between price and accuracy is the typical photogrammetric solution, using combined digital images to build a point cloud, but which has the disadvantage of complex training of staff to correctly take the images.

In 2020, Apple Inc. released the first phone with innovative built-in LiDAR (Light Detection And Ranging) depth sensors and an enhanced augmented reality (AR) application programming interface (API). LiDAR makes time-of-flight or phase-shift measurements of laser pulses to determine the distances to an object. As a result, LiDAR sensors can be used to generate a depth map image of an object (Heinrichs et al., 2021). This introduced a relatively inexpensive competitor to the current hardware solutions for inventory work requiring only moderate accuracy. The solution by Apple Inc. is not a surface scan in the sense of a TLS device, but it can create a colored point cloud at a scale of 1:1. The device combines positional data with time and a depth map so that a 3D model can be built. All these advantages have led to iPad Pros and iPhones with built-in LiDAR being tested for inventorying of different types of objects, including natural forests (Gollob et al,. 2021, Mokroš et al., 2021), cliffs (Luetzenburg et al., 2021), and rocky slopes (Riquelme et al., 2021). Apple's LiDAR-enabled devices have found applications in many earth science works where a 10 cm accuracy of the acquired point cloud is required, and where the cost and ease of acquiring a 3D model of the object are the primary arguments in the selection of the measurement device. Researchers are going deeper by testing and comparing the LiDAR and TrueDepth functions on the iPad Pro with an industrial Artec Space Spider 3D scanning solution on small objects requiring high measurement precision, looking at the effects of color, shape and position tolerance (Vogt et al., 2021). While the authors concluded that in general the industrial scanner should still be the preferred solution for measuring small objects, they emphasized that the iPad Pro has the advantage of being widely available. The authors also highlighted that although the scanned objects obtained with the iPad Pro had higher standard deviations than those scanned by the Artec Space Spider, the iPad Pro offered the ability to scan with a usable accuracy at a much lower cost.

2. MATERIAL AND METHODS

2.1. Study area

The accuracy, cost and popularity of scanning with the Apple LiDAR solution presented in the introduction led the authors of this paper to test the LiDAR built-in to the Apple iPhone 13 Pro and compare it to a Zoller + Fröhlich 5006h precision ground-based scanner in typical inventory work. Three-dimensional models in the form of point clouds from both devices were transformed into a uniform coordinate system from white and black targets placed on the objects. The point clouds were then compared to each other using CloudCompare software. The M3C2 plugin for Multiscale Model to Model Cloud Comparison is a unique way to compute signed (and robust) distances directly between two point clouds without meshing or gridding. Furthermore, the algorithm computes the local distance between two point clouds along the normal surface direction, which tracks 3D variations in surface orientation and estimates a confidence interval for each distance measurement depending on point cloud roughness and registration error (Lague et al., 2013). In addition to a direct comparison of the two point clouds, a comparative analysis was made of the accuracy of selected object dimensions in the point clouds. From an office space, the height and width of the room and the doorway were selected as typical dimensions, for example: architectural details such as the arches in lintels and vaults, the chord length between the start and end points of the arch, the height of the arch, the radius of the arch, and the average distance of the points from the theoretical shape of the arch. For each of the analyzed dimensions, 10 independent readings were taken from which the mean value of the dimension was determined (formula 1), along with the standard deviation of the mean value (formula 2) and the mean error (formula 3).

$$\acute{x} = (x_1 + \cdots + x_n)/n \tag{1}$$

$$\sigma_{\overline{x}} = \sqrt{\frac{\Sigma_i^n \left(x_i| - \overline{x}\right)^2}{n(n-1)}} \tag{2}$$

$$m = \sqrt{\frac{\Sigma_i^n \left(x_i| - \overline{x}\right)^2}{n}} \tag{3}$$

where
x_i - the value of the i-th measurement,
$\overline{x}$ - the average x-value for the entire measurement series,
n - number of measurements in the series.

In addition, for the suspended ceiling and a flat section of white wall, the best-fit plane algorithm in the CloudCompare software was used to evaluate its accuracy in each point cloud.

The subject of the first experimental measurement was an office room (Figure 1) of approximately 30m^2 equipped with typical office furniture.

Figure 1 Colored point cloud view of the section of an office room scanned by the iPhone 13 Pro

The second measurement was a fragment of the cloisters of the main hall of Warsaw University of Technology (Figure 2). These objects were selected as representative for the basic tasks of building objects inventory, i.e. dimensioning an office space and exemplary architectural details.

Figure 2 Colored point cloud of a fragment of the main hall of Warsaw University of Technology scanned by the iPhone 13 Pro

2.2.Instrumentation and data collection

In this study, a Z+F 5006h terrestrial laser scanner (Table 1) and an iPhone 13 Pro (Table 2, Figure 3) with 3DScanner App were used.

Table 1 Selected technical parameters of the Z+F 5006h terrestrial laser scanner (based on information brochure, www.zf-laser.com)

Ambiguity interval:	79 m
Min. range:	0.4 m
Resolution range:	0.1 mm
Max. data acquisition rate:	1,016,727 pixel/sec
Linearity error up to 50 m:	≤ 1 mm
Range noise at 10 m: - Reflectivity 10% (black): - Reflectivity 20% (dark grey): - Reflectivity 100% (white):	 1.2 mm rms 0.7 mm rms 0.4 mm rms
Resolutions: - Preview - Middle - High - Super high - Ultra high	Scanning time: - 25 sec - 1 min 40 sec - 3 min 22 sec - 6 min 44 sec - 26 min 44 sec
Illumination:	All conditions from darkness to daylight
Dimensions and weights Scanner (w x d x h)/weight:	 286 mm x 190 mm x 412 mm/14 kg

Table 2 Selected specifications of Apple's iPhone 13 Pro

Basic data	
Display	6.1", 2532 x 1170px, OLED, Super Retina XDR
Built-in memory [GB]	128
Camera LED lamp	Rear 3 x 12 Mpx, Front 12 Mpx Yes
Processor model Number of processor cores Operating System System version	Apple A15 Bionic Six-core iOS iOS 15
Camera functions	Bokeh effect, Geolocation, HDR with Dolby Vision support, Optical Image Stabilization, Panorama, Red-eye reduction, LiDAR, Wide angle lens, Telephoto lens, Night mode, Portrait mode, Ultra wide angle lens, Continuous shooting
Physical Specifications	
Thickness [mm] Width [mm] Height [mm] Weight [g]	7.65 71.5 146.7 203

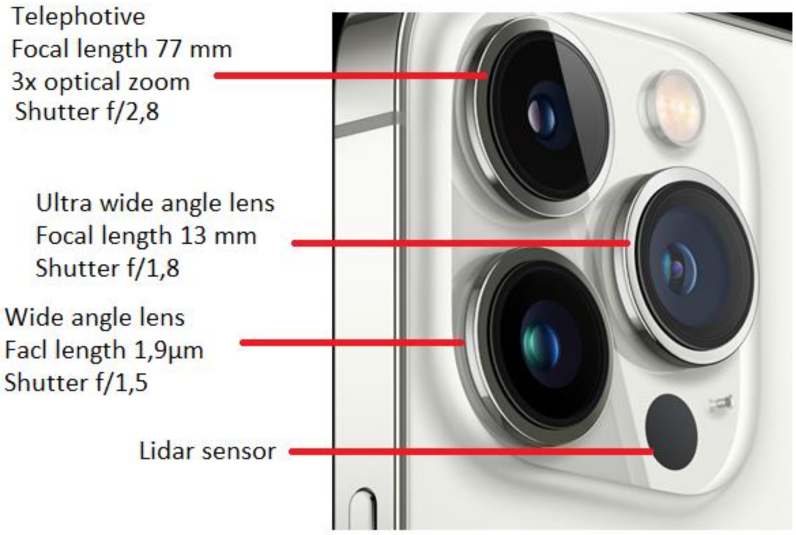

Figure 3. View of Apple's iPhone 13 Pro rear camera with a description of the components

Laser scanning using the iPhone 13 Pro can be implemented using a variety of applications: 3D Scanner App, Polycam, SiteScape , LiDAR Scanner 3D, Heges, LiDAR Camera, 3Dim Capture, Forge. The 3D Scanner app used for the research in this study appears most often in scientific publications (Mokroš et al., 2021; Gollob et al., 2021).

The 3D Scanner App can process photos and videos in real-time to create 3D models, including high-resolution and textures. Supported data export formats in the app are: XYZ color, PLY, PTS, LAS, LAS Geo-Referenced, E57, PCD. Scanning with this application is inversely related to the speed of movement, with reducing quality of scanning as the speed rises.

When a scan is complete, a texture will be automatically applied if the object is small, but for large objects they must be textured manually from the scan view. In the application there are two options to set the resolution: low resolution mode and high resolution mode. Low Resolution Mode is the simplest way to capture a scan and has fewer options and is recommended for capturing large areas such as a house. High Resolution Mode is more suitable for smaller objects such as a couch or chair.

High resolution options:

Confidence – options for thresholding the data coming in from the sensor [Choosing HIGH only keeps the best quality data, but reduces the amount of data available (e.g. far away values will be discarded)].

Max Depth / Range – discards LiDAR data beyond a certain distance. Limiting range reduces scan size and increases accuracy.

Resolution – 5mm to 20mm; Lower values (5 mm) mean higher resolution, but also limited scan size. 10-15 mm is recommended.

Masking – NONE, OBJECT or PERSON – this feature masks LiDAR data based on the type of object in view. OBJECT attempts to isolate prominent objects in view. For best results, keep the object fully in view on a simple background without other clutter.

3D Scanner App for Mac is a desktop tool for processing photos and videos into 3D models using the power of Photogrammetry in the new Object Capture API on supported hardware.

All scans in the experiment were performed using the following parameters:

- iPhone 13 Pro with 3D Scanner App (Laan Labs, New York, USA) in High Resolution mode: max depth = 5 m; resolution = 10 mm; confidence = high; masking = off.
- Z+F 5006h ground-based laser scanner: resolution = superhigh, quality = normal, laser mode = normal.

The iPhone 13 Pro scanning process was carried out in a manner analogous to the terrestrial laser scanner operation, i.e., the operator with the device stood in the place from which the measurement position was planned and then holding the smartphone in his hand rotated around his axis for 360°. For the office room, the measurements were carried out from three positions, while for the cloisters of the main auditorium of Warsaw University of Technology the measurement was conducted from four positions.

3. RESULTS

The first stage of the research comprised a comparison of selected characteristic dimensions of the two objects. For each of the analyzed dimensions, 10 independent readings were taken from which the average value of the dimension was determined, along with the standard deviation and average error. Table 3 presents the results of measurements of selected elements of the office room and their mean value, standard deviation and mean error. The least difference in dimensions was recorded for the height of the inner opening of the entrance door frame, and the largest for its width. This difference was due to the quality of the representation of this element in the point cloud from the iPhone 13 Pro. Figure 4 shows a cross-section through the point cloud extracted from the iPhone in which it is clear that both parts of the door frame were rounded (especially the left side), which affected the accuracy of the measurement. It should be noted that the basic dimensions of the room itself obtained from both devices differed by 2-4 cm. It should also be noted that the iPhone data had a larger standard deviation and mean error, indicating less repeatability. Both the standard deviation and mean error were less than 1.5 cm, which should be considered a good result (satisfactory for most inventory tasks).

Analogous analyses were performed for selected parameters of the curved lintel (Table 4). In this case, all the average dimensions from both devices differed by less than one centimeter (The average error for the radius of the arch from the iPhone 13 Pro exceeded 2 cm.) The radius of the arch was determined by fitting a circle using the method of least squares into the cross-section through the point cloud representing the lintel (Figure 5), which avoided the influence of the dimensional accuracy on the measurement results.

Table 3. Summary of the results of the measurements of selected elements of the office space and their mean value of dimension, standard deviation of the mean value and mean error value**.**

Element to be measured	Dimensions of entrance door frame interior opening				Basic room dimensions			
	Height [m].		Width [m].		Height [m].		Width [m].	
	iPhone 13 Pro	Z+F 5006h	iPhone 13 Pro	Z+F 5006h	iPhone 13 Pro	Z+F 5006h	iPhone 13 Pro	Z+F 5006h
1	2.476	2.486	1.291	1.305	4.339	4.396	3.376	3.347
2	2.474	2.475	1.266	1.307	4.396	4.395	3.389	3.344
3	2.475	2.477	1.286	1.305	4.332	4.391	3.376	3.349
4	2.470	2.482	1.267	1.305	4.352	4.392	3.377	3.356
5	2.471	2.475	1.272	1.307	4.349	4.394	3.360	3.341
6	2.464	2.480	1.258	1.306	4.342	4.392	3.359	3.350
7	2.468	2.481	1.286	1.305	4.355	4.407	3.351	3.355
8	2.475	2.477	1.257	1.306	4.352	4.406	3.364	3.345
9	2.478	2.477	1.283	1.307	4.358	4.398	3.353	3.358
10	2.472	2.480	1.292	1.304	4.338	4.382	3.361	3.349
Average	**2.472**	**2.479**	**1.276**	**1.306**	**4.351**	**4.395**	**3.367**	**3.349**
SD	**0.001**	**0.001**	**0.004**	**0.000**	**0.006**	**0.002**	**0.004**	**0.002**
Mean error	**0.004**	**0.003**	**0.013**	**0.001**	**0.018**	**0.007**	**0.012**	**0.005**

Figure 4. Horizontal section of a door frame scanned with iPhone 13 Pro

The remaining research presented in this paper covers the office room. The object was scanned with an iPhone 13 Pro and a Zoller + Fröhlich 5006 h precision ground-based scanner. The 3D model point clouds obtained from both devices were transformed to a uniform coordinate system based on white-on-black targets distributed on the objects. The transformation resulted in an RMS error = 0.029 m (data from the Z+F 5006h instrument was used as the reference cloud). The point cloud transformation matrix is shown below (4).

$$\begin{vmatrix} 1.000 & 0.022 & -0.001 & 0.067 \\ -0.022 & 1.000 & 0.008 & -0.006 \\ 0.001 & -0.007 & 1.000 & 0.085 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{vmatrix} \tag{4}$$

Table 4. Summary of results of measurements of selected parameters of the arch-shaped lintel and the mean value, standard deviation and mean error value.

Element to be measured	Length of the chord between the start and end points of the arc		Arch height		Curve radius	
	iPhone 13 Pro	Z+F 5006h	iPhone 13 Pro	Z+F 5006h	iPhone 13 Pro	Z+F 5006h
1	1.921	1.943	0.868	0.878	1.011	0.972
2	1.901	1.940	0.874	0.876	0.985	0.971
3	1.922	1.929	0.868	0.876	0.930	0.971
4	1.923	1.929	0.870	0.878	1.000	0.971
5	1.939	1.919	0.873	0.870	0.987	0.971
6	1.924	1.912	0.871	0.876	1.013	0.971
7	1.944	1.932	0.867	0.876	0.992	0.973
8	1.929	1.922	0.879	0.871	0.975	0.976
9	1.919	1.914	0.872	0.887	0.987	0.973
10	1.935	1.931	0.877	0.880	0.990	0.974
Average	**1.927**	**1.927**	**0.871**	**0.877**	**0.988**	**0.972**
SD	**0.004**	**0.003**	**0.001**	**0.001**	**0.007**	**0.001**
Mean error	**0.012**	**0.010**	**0.004**	**0.004**	**0.023**	**0.002**

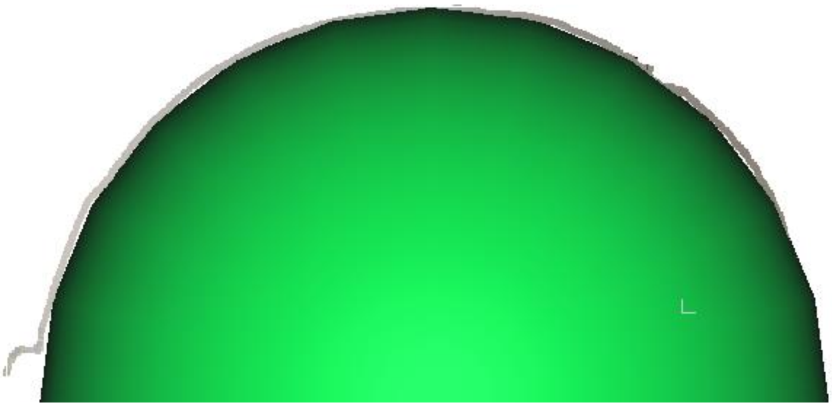

Figure 5. View of a fragment of the circle fitted into a cross-section of the point cloud from the iPhone 13 Pro representing an arch in the lintel of the cloisters of the main auditorium of Warsaw University of Technology

The point cloud transformation results should be taken as satisfactory. Obtaining better results is difficult due to the lower accuracy of the point cloud obtained from the iPhone 13 Pro. Figure 6 shows a fragment of a vertical section through both registered and mutually oriented point clouds. As can be seen, the point cloud from the iPhone 13 Pro represents a room that is about 7 cm narrower in the selected cross section. Such a difference significantly hinders the mutual orientation of the point clouds.

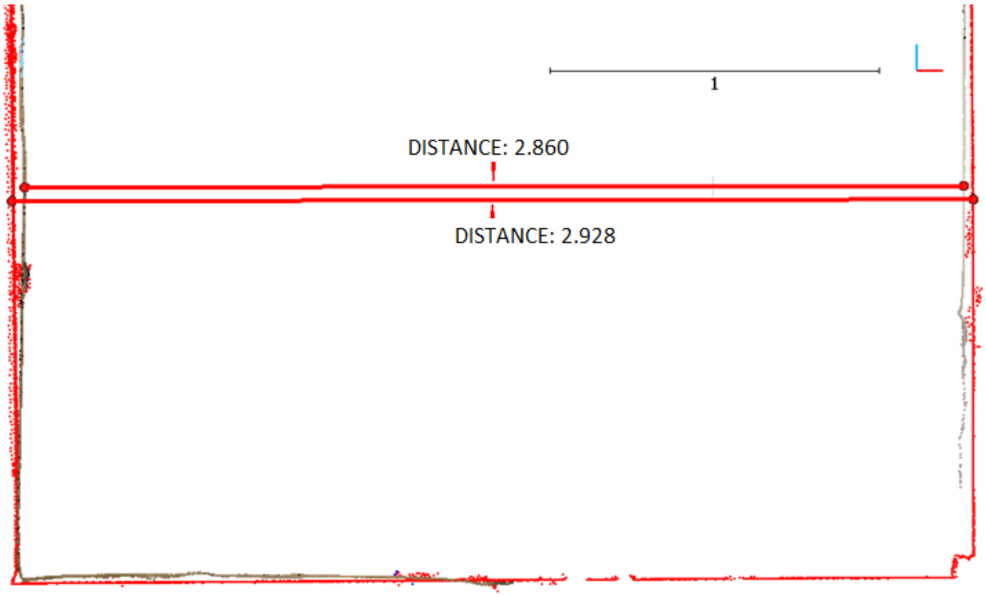

Figure 6. Example cross-section through the point clouds of an office room showing the differences in registered points. The point cloud from the Z+F 5006h is in red and the one from iPhone 13 Pro in real color

In analyzing the acquired data, it was found that the differences in the two point cloud models were mainly due to the non-planarity and non-rectilinearity of the point cloud from the iPhone 13 Pro. This was also evident in the suspended ceiling of the office room, where the frame of the panels formed an approximately rectangular grid of squares. Figure 7 compares the point cloud view of the aforementioned ceiling from the Z+F 5006h and from the three stations registered with the iPhone 13 Pro. It can be clearly seen that on the data acquired from the iPhone, the rectilinearity of the coffer casing was not preserved.

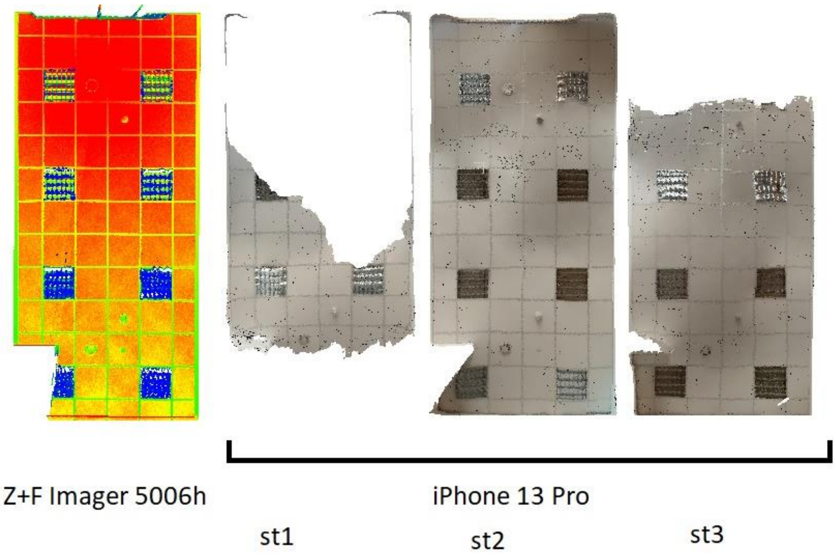

Figure 7. Ceiling view of the office room: point cloud from the Z+F 5006h and from three stations registered with the iPhone 13 Pro

The oriented point clouds were then compared using the Multiscale Model to Model Cloud Comparison (M3C2) algorithm in CloudCompare (Figure 8). Data from the Z+F 5006 h was used as the reference cloud, and the comparison cloud was from the iPhone 13 Pro**.** Distances facing the room floor were taken as positive. From the distance difference map produced, it was found that the distance differences were mostly between -0.015 m and 0.030 m. Most of the points acquired with the iPhone were below the ceiling level inventoried with the precision scanner.

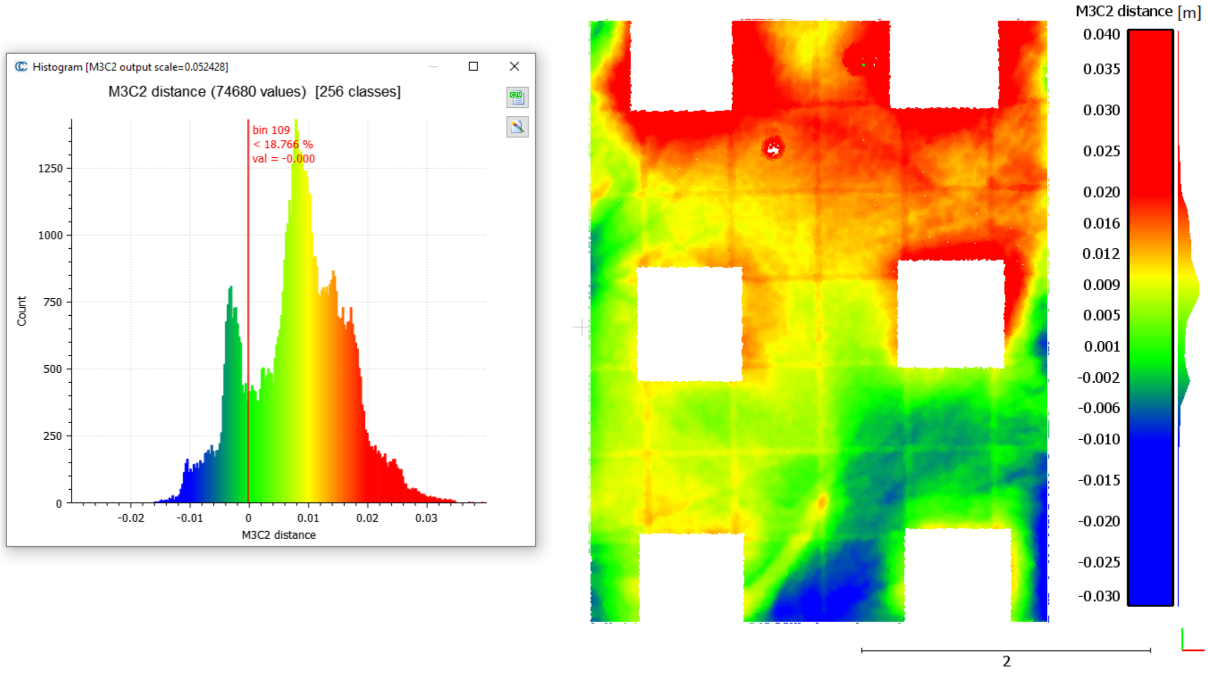

Figure 8. M3C2 algorithm comparison of point clouds for a section of the office room ceiling. The reference cloud was acquired with the Z+F 5006h, the study cloud was from the iPhone 13 Pro

In the next step, an analysis was made of the distance of the measured points from a horizontal plane at a height of 2.400 m (below the actual height of the ceiling). Thanks to such a comparison it was possible to determine the planarity of the measured ceiling fragment. For differences from 0.075 m to 0.130 m the same color scale was used for the data from both instruments. As can be seen, the data from the Z+F 5006h (Figure 9) indicated a slight deformation of the ceiling of about 1.5 cm. The data from iPhone 13 Pro (Figure 10) was characterized by much greater deviations from level by about 5 cm. It is worth noting that both studies indicated similar areas in which that part of the ceiling was slightly lower than the rest of the ceiling.

It is also worth noting that the largest deviations from horizontal for the iPhone 13 Pro occurred around the white ceiling squares in which the room lighting was located (Figure 10). These differences were due to the measurement method and the way the model was generated from photos and a distance grid by the 3D Scanner App. As a result, at a place with edges or changes in the direction of the planes, averaging of the data manifested as a rounded (curved) edge.

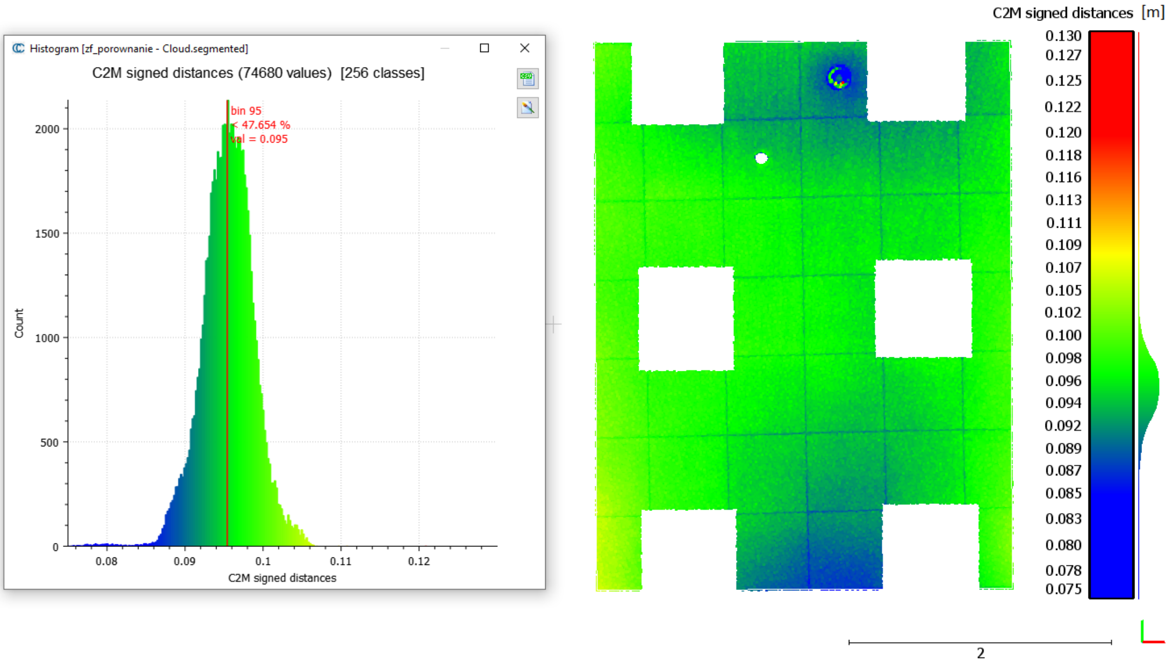

Figure 9. Map of point distances from a horizontal plane at a height of 2.4 m for a fragment of the office room ceiling scanned with a Z+F 5006h

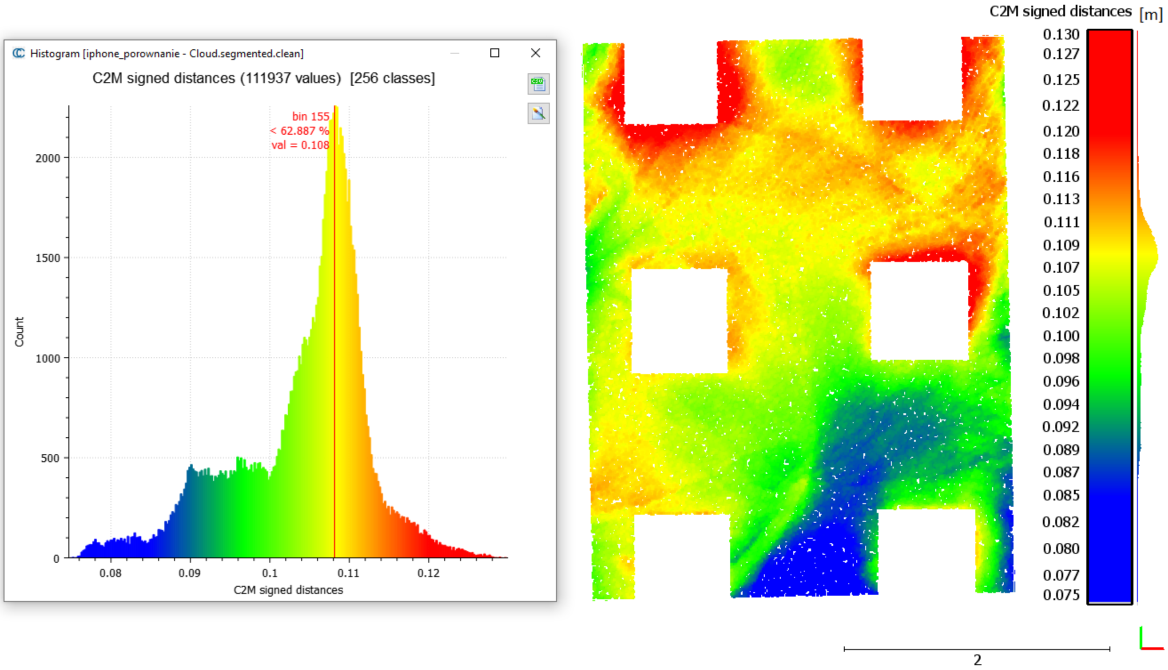

Figure 10. Map of point distances from a horizontal plane at a height of 2.4 m for the office ceiling fragment scanned with the iPhone 13 Pro

The analysis of flatness of a fragment of the office room wall was performed. Due to the difference in width of the room as scanned by both instruments, and problems with precise orientation, it was decided to fit the planes independently into each point cloud and then to determine the distance between the point cloud and the fitted plane. Different size distributions of the determined distances were produced. The data from the Z+F 5006h were within 0.6 cm (Figure 11), while the iPhone 13 Pro data exceeded 1.0 cm (Figure 12), which indicates the lower precision of the measurement using the iPhone.

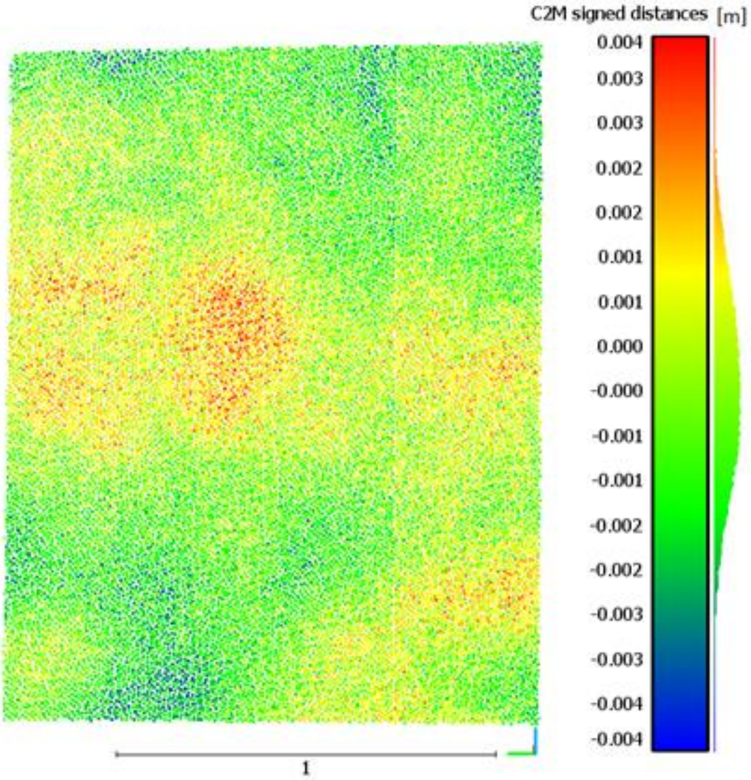

Figure 11. Distance map of the point cloud points from the Z+F 5006h from the plane fitted into the analyzed point cloud. The fit error of the RMS plane = 0.001 m, while the plane's normal vector is (0.99992; 0.01069; 0.00595)

The results of the conducted tests show the differences obtained between the point cloud analysis from the iPhone 13 Pro and the Z+F 5006h. It should be stressed that with regard to the metric aspect of the presented results, the discrepancies do not exceed single centimeters, which is a sufficient accuracy for many applications in the field of building inventory and architectural-construction of objects. The presented discrepancies result mainly from the method of point cloud acquiring by the iPhone 13 Pro smartphone, which does not exclude its use for many inventory tasks. The analyses presented in this paper are intended to show the problems and limitations that occur. Point clouds acquired with iPhone 13 Pro will have less precise mapping of edges and will not meet the precise inventory of small architectural details, and their accuracy will be at the level of 1-2 cm, which is sufficient for conceptual studies and obtaining the basic dimensions of rooms, for example for the purpose of creating a database of premises, or preparation of data for payments for utilities based of the area of commercial premises.

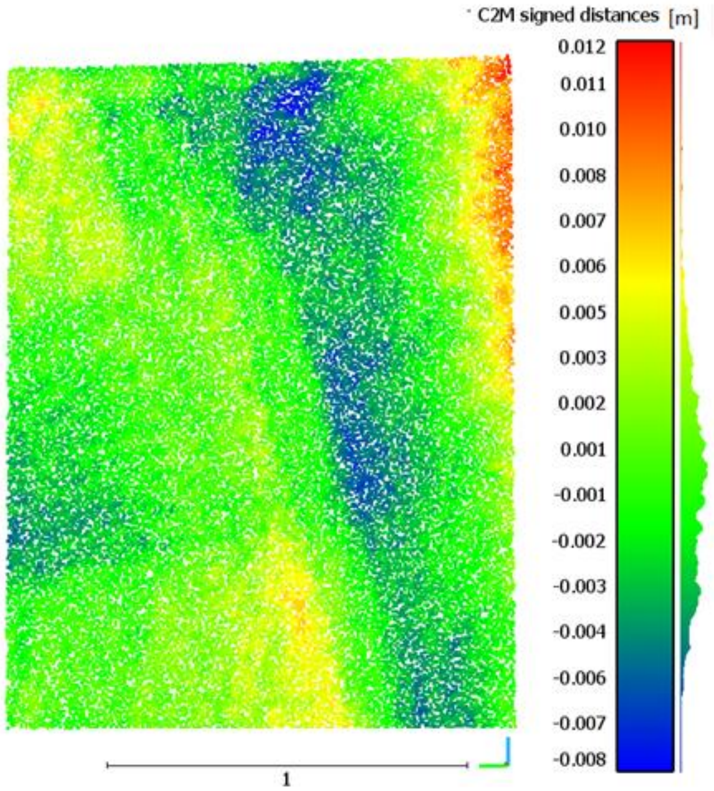

Figure 12 Distance map of the point cloud points from the iPhone 13 Pro from the plane fitted into the analyzed point cloud. The fit error of the RMS plane = 0.003 m, while the plane's normal vector is (0.99999; -0.00508; -0.00023)

4. DISCUSSION

In this paper a smartphone iPhone 13 Pro was used with the 3D Scanner App (Laan Labs, New York, USA), and the acquired data used to evaluate the accuracy of the LiDAR technologies embedded in the device in comparison with a Z+F Imager 5006h precise terrestrial laser scanner. This paper attempts to assess whether the Apple iPhone 13 Pro and 3D Scanner App solution can be used to perform building and architectural inventories. A typical office room and a fragment of the cloisters of the main auditorium of the Warsaw University of Technology were used as test objects. These objects were scanned by each equipment at the same time, black and white checkerboards were placed at different heights for mutual registration and superimposition of point clouds. The results were analyzed and compared using CloudCompare software tools.

With the use of LiDAR technology in Apple devices, a number of publications have appeared in world literature evaluating the possibility of using this solution for tasks. The main factor encouraging us to take up this topic is the price of the scanning device. Apple smartphones or iPads cost about a thousand EURO, while professional scanning devices cost at least tens of thousand EURO. Hence authors have tried these cheaper solutions to obtain three-dimensional point clouds models. These attempts have led to differing conclusions. Vogt et al., (2021) evaluated the scanning accuracy of different colored Lego bricks with an iPad Pro (2020) and found that this LiDAR technology is impractical for scanning such small objects. The authors pointed out that the Apple LiDAR depth data is combined with accompanying color (RGB) data using artificial intelligence to create a depth map. In addition, the mesh of the depth map consists of triangles with a relatively large mesh dimension, and as a result, LiDAR can be used to support Augmented Reality or to scan large objects, such as rooms, but is not applicable for scanning very small objects. Similar conclusions have been drawn by other authors who have attempted to use Apple devices for tasks requiring much less precision, such as the measurement of forests (Mokroš et al., 2021) or geomorphological forms (Riquelme et al., 2021). In the context of forest inventory work, the authors point out that the iPad Pro is a solution that provides a point cloud immediately oriented in the field so operators can get results in real time. On the other hand, they emphasize that the data acquisition must be done skillfully to avoid rescanning previously scanned areas, making it less practical in the field, especially in dense diverse forests. They also highlighted that the performance of the iPad Pro with LiDAR sensor possessed DBH estimation accuracy and tree detection rate close to TLS results, which is a very good result (Mokroš et al., 2021). In the case of scanning geomorphological forms, the authors point out the great potential of Apple's solution, while highlighting some concerns and problems. First of all, the authors note that a key factor affecting the completeness of the data is the way it is collected. During scanning with the Apple devices, the distance between the surface and the device was less than 3 m (the allowable distance is 5 m), which, compared to terrestrial laser scanners that can reach a distance of up to 200 m, is quite a limitation to the use of this technology. Another important aspect is the data acquisition time (just four minutes), regardless of the capture time (i.e. scanning or photographing (recording digital images), which is unlimited in other devices. It should be emphasized that the results of scanning geomorphological forms led to the conclusion that smartphones and iPads equipped with LiDAR functionality may soon become widely used for these tasks (Riquelme et al., 2021).

The conclusions presented in discussions in various publications and scientific research papers match the results obtained in the context of the inventory of building objects. In the case of research undertaken by the authors, measurement time and scanning distance were a problem and a kind of disadvantage in relation to typical terrestrial laser scanners. The obtained accuracy could be considered reliable in the range of 1 cm - 2 cm, which is mainly due to the effect of the iPhone 13 Pro rounding some edges in the point cloud model. Additionally, the authors point out that the care in taking the measurement itself is crucial, i.e. the stability of the iPhone during measurement (it is suggested to perform the work using a photographic tripod) and the speed of turning or moving the device. Too rapid movements result in shape loss which in our study was visible in the asymmetry of the scanned arc.

5. CONCLUSIONS

The presented research and discussion of the obtained results indicate a great potential of the Apple iPhone 13 Pro with the built-in LiDAR function to inventory buildings. However, it is necessary to remember about the necessity of using an appropriate methodology of performing measurements (acquiring spatial data) and about technological limitations. The authors would like to emphasize that scanning performed with a smartphone will not replace precise solutions based on terrestrial laser scanning or classical surveying. This is mainly due to the fact that the accuracy achieved with the iPhone 13 Pro is reliable to a single centimeter, and thus this type of device can be used for work of limited accuracy, such as visualization or reconstruction concepts of an object, rather than precise tasks. The cost of scanning with an iPhone is low enough to certainly have a positive impact on the popularity of using point clouds and their derivative products in construction and other fields.

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Janina Zaczek-Peplinska obtained her doctorate in the field of geodesy and cartography in 2008 and habilitated doctor in 2019 at the Faculty of Geodesy and Cartography of the Warsaw University of Technology. She is employed as a university professor at the Department of Engineering Geodesy and Measurement Systems, of which she is the head. Author or co-author of over one hundred and twenty scientific publications (and conference presentations) related to the analysis and use of classic geodetic measurement data, displacement measurements, the use of terrestrial laser scanning in engineering geodesy, and surface condition assessments based on spectral analysis of measurement data. She specializes in geodetic monitoring of hydrotechnical facilities. She has participated in numerous measurement and research works related to the determination of displacements and assessment of the technical condition of engineering facilities. In the years 2013-2015 she was a scholarship holder of the Center for Advanced Studies of the Warsaw University of Technology. He collaborates with the Institute of Geodesy and Geoinformation Science TU Berlin.

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