Assessing the effectiveness of LiDAR-based apps on Apple devices to survey indoor and outdoor medium sized areas

Daniele Treccani[1], Andrea Adami[1], Luigi Fregonese[1]

[1] UNESCO Research Lab, Dept. of Architecture, Built environment and Cosntruction engineering,
Politecnico di Milano, Mantova Campus, Piazza C. d'Arco 3, 46100 Mantova, Italy
(daniele.treccani, andrea.adami, luigi.fregonese)@polimi.it

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Abstract

In 2020, Apple started to include a LiDAR (Light Detection And Ranging) sensor on its high-end mobile devices. Since the introduction of the sensor, a large number of apps exploiting it have populated the iOS App Store. Therefore, Apple devices with a LiDAR sensor have seen increasing applications for efficient, low-cost spatial analysis and 3D modeling of small objects, rooms, and small areas. In this context, it becomes interesting to understand the potential of this sensor exploited by existing apps for surveying not only small areas, but also medium-sized indoor and outdoor areas. The study here presented evaluates the effectiveness of five iOS LiDAR-based apps for surveying medium-sized indoor and outdoor environments using Apple devices. The research used two test areas—a university building corridor (indoor) and a narrow urban street (outdoor)—to examine the performance of each app against a reference dataset from a Terrestrial Laser Scanner (TLS). The study explores each app's capabilities, considering settings, point cloud density, accuracy, and usability across two survey path strategies: a closed loop and a zigzag. Results highlight that while mobile LiDAR apps on Apple devices facilitate low-cost, fast, accessible surveys, they exhibit in some areas errors on the order of 10 centimeters, while in others, on the order of 1 centimeter. The final result was very much influenced by how the raw data was handled by the apps, and it was noted that for medium-sized areas (both indoor and outdoor) the apps that produced better results were the ones benefitting from loop-closure to reduce trajectory drift. Based on the results, this approach could support urban management, road assessments, and other applications where rapid data capture is required and medium accuracy is sufficient.

1. Introduction

Since 2020, when Apple introduced a LiDAR (Light Detection and Ranging) system in its mobile devices —starting with the iPhone 12 and 13 Pro series and the iPad Pro— there has been a notable increase in the number of surveying applications available on the iOS App Store. These applications utilize the integrated LiDAR technology, frequently in combination with data from the built-in camera or the onboard GNSS sensor to enhance accuracy and detail, allowing users to produce detailed, colorized point clouds and meshes.

The use of embedded low-cost sensors in mobile devices for surveying presents an opportunity for conducting quick and affordable surveys. However, this convenience comes with a trade-off: while these mobile solutions are accessible and easy to use, the accuracy may not match that of traditional, high-end surveying equipment. Furthermore, each available app may process the acquired data in different ways, producing different results. Therefore, it is essential to investigate both the precision of these tools and the diverse range of applications available, while also considering their usage. This understanding will shed light on the evolving role of mobile-based LiDAR in accessible and efficient surveying technology.

In the documentation of the built environment context, researchers have investigated the feasibility of mobile devices for scan-to-BIM processes and of indoor outdoor environments. Teo and Yang (2023) evaluated the accuracy of an iPad Pro's LiDAR in indoor mapping for scan-to-BIM applications. They used '3D Scanner App' and 'RTAB-Map' apps. They found out that scanning a smaller area resulted in better accuracy, and that LiDAR sensor is capable of producing accurate point clouds adequate for BIM only in certain conditions. With a similar purpose, Díaz-Vilariño et al. (2022) evaluated the use of Apple devices for 3D indoor/outdoor mapping and for scan-to-BIM workflows. They used '3D Scanner App' and surveyed an indoor environment (2 adjacent rooms) and outdoor environment (a portion of a sloped street). Based on their results, they concluded the device was more suitable for mapping small environments. Other researchers focused on the survey of cave environments; Kartini et al. (2023) surveyed a graffitied cave and compared Stonex F6 handheld scanner and '3D Scanner App' on iPhone. They concluded that iPhone had better radiometric data, but Stonex F6 produced more dense point clouds. Similarly Kartini et al. (2022) evaluated '3D Scanner App', 'EveryPoint', and 'SiteScape' apps for the documentation of caves. Some researchers also investigated the combined use of mobile devices with low-cost RTK (Real Time Kinematic) GNSS (Global Navigation Satellite System) receivers. Martino et al. (2024) used and compared 'Pix4Dcatch' app with and without viDoc RTK rover and 'Scaniverse' app, tested on a statue and a portion of a portico. The aim was the expeditious documentation of endangered built heritage. Focusing on road environments, Suleymanoglu et al. (2023) used 'Pix4Dcatch' in combination with viDoc RTK Rover for road assessment. Their method could be used for road boundary extraction and cross-slope evaluation. Focusing on small areas, Tamimi and Toth (2023) used an iPhone mounted on a scooter to acquire data while moving. They used 'pix4Dcatch' app in combination with viDoc RTK Rover in conjunction with Pix4Dmatic software. Some researchers focused also on the comparison of different apps or different LiDAR-equipped mobile devices. Teppati Losè et al. (2022) evaluated three different apps ('SiteScape', 'EveryPoint', and '3D Scanner App') on three different scenarios: a statue, a decorated room, and an external facade. Each tested application provided different results, highlighting the crucial role of the software component when exploiting the same hardware setup. Instead Costantino et al. (2022) tested a Huawei and an iPhone for surveying various objects, using the '3D live scanner pro' for Android and '3D Scanner App' for iOS. They tested various objects and concluded that mobile devices have proven to be useful tools for scanning objects and environments in urban scenarios.

The research conducted reveals that previous case studies primarily focused on small to medium-sized sites with various objectives, ranging from urban and outdoor applications to indoor scenarios related to the scan-to-BIM process. While a range of applications were employed for data collection, each processed data uniquely, resulting in varied outputs even when the same data acquisition system was used. Additionally, when compatible, the use of an RTK rover receiver notably enhanced the accuracy of survey results; however, not all available applications supported integration with such systems.

In light of these findings, testing the Apple LiDAR system in medium to larger areas is of particular interest, as is evaluating different applications to analyze how they handle diverse environments and surveying methodologies. Therefore, in this study, we selected five iOS applications (three free and two fee-based) from the App Store to assess their effectiveness and compare outcomes. Testing was conducted in two medium-sized sites—one indoor and one outdoor—using only an Apple device equipped with a LiDAR sensor, without supplementary topographic instruments. The resulting survey data from each app was then compared with a reference dataset collected via a Terrestrial Laser Scanner (TLS).

2. Materials

2.1 Test areas description

Two testbeds suitable for the purpose of the research were identified. The first case study (case A) concerned an indoor environment: a portion of the university building (see Figure 1) consisted of a long corridor (approximately 40 meters in length, for a width of 2 meters) overlooked by 5 small rooms (approximately 16 square meters each). During the survey activities one room was not accessible and therefore not surveyed. The particularity of this case study was the great homogeneity in the coloring of the corridor (ivory and with a very constant geometric shape with few three-dimensional elements) and the presence of high, vaulted ceilings (cross vaults for the rooms and barrel vaults for the corridor).

The second case study (case B) concerned an outdoor environment: a portion of the street, formed by two stretches with an L-shaped plan and a total length of 72 meters (see Figure 2). The street was located in the historical center of Mantua and was therefore characterized by being very narrow (only one lane, for an average width of 4 meters), and with buildings placed side by side to form a single continuous façade on the street.

2.2 Apple device and iOS Apps selection

The Apple device used for this study was an 11-inch iPad Pro (second generation). According to Luetzenburg et al. (2021), Apple devices employ a Vertical Cavity Surface Emitting Laser (VCSEL) that emits near-infrared light in a 2D array, and the

Figure 1. Plan view and pictures of the first test area concerned an indoor environment. The area is a corridor with several rooms. The survey was conducted using two different paths: a closed loop (path A1, blue), and an open path with a zigzag movement (path A2, red). The blue circle indicates the start point of both paths, and the endpoint of path A1; the red circle indicates the end point of path A2. The green circles indicate the positions of the markers in the test area.

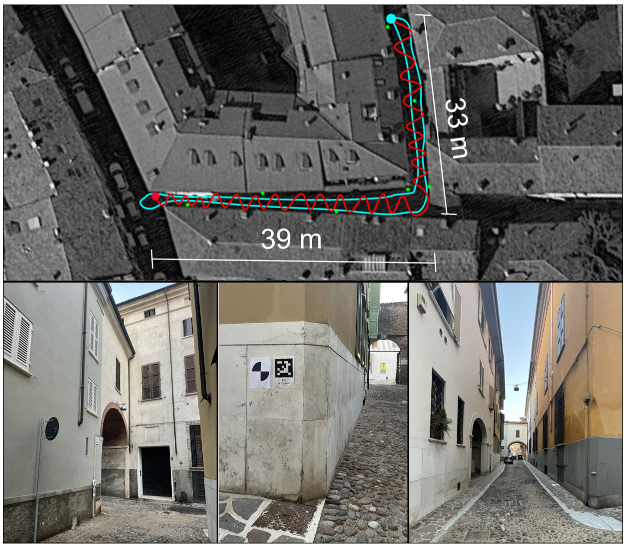

Figure 2. Map view and pictures of the second test area, concerning an outdoor environment. The area is a portion of the road. The survey was conducted using two different paths: a closed loop (path B1, light blue), and an open path with a zigzag movement (path B2, red). The light blue circle indicates the start point of both paths, and the endpoint of path B1; the red circle indicates the end point of path B2. The green circles indicate the positions of the markers in the test area.

direct time of flight (dTOF) of the emitted pulses is measured using a Single Photon Avalanche Photodiode (SPAD). The combination of increased VCSEL power density and SPAD technology enables flash-LiDAR functionality in consumer devices like the iPad and iPhone. The VCSEL projects an array of 8×8 points, diffracted into a 3×3 grid, yielding 576 total points. With a maximum range of 5 meters, the point density decreases logarithmically with distance, from 7,225 points per square meter at 25 cm to 150 points per square meter at 250 cm. Authors of Luetzenburg et al. (2021) did not find significant differences between the iPad and iPhone LiDAR systems in terms of emitted points, point density, or focal length.

In the current market of applications for the Apple iPhone or iPad Pro, i.e. those available in the iOS App Store, it is possible to identify a large number that make use of the LiDAR system on board the Apple device. The use of LiDAR is generally functional for those applications that propose Augmented Reality activities or experiences, but it is also possible to find a large number of applications devoted to 3D surveying. Such applications make use of photogrammetry techniques, also in combination with technologies that make use of artificial intelligence (e.g. Gaussian splatting), but above all make use of LiDAR.

In order to define the apps to be used in this study, we decided to inspect the App Store using the search key 'LiDAR'. The apps present and available were many, a choice had to be made, and it was decided to initially search for apps with higher user ratings and a higher number of reviews. The search results were then filtered by looking for apps that allow (or state that they can be used to) survey medium to large areas. By cross-referencing this information with existing scientific literature, and under the assumption of working only with the Apple device without other topographic instruments, the following apps were selected (for further details see Table 1): '3D Scanner App' (www.3dscannerapp.com); 'Dot3D - LiDAR 3D Scanning' (www.dotproduct3d.com/ios); 'Polycam 3D Scanner, LiDAR, 360' (www.poly.cam); 'RTAB-Map - 3D LiDAR Scanner' (introlab.github.io/rtabmap); 'Scaniverse - 3D Scanner' (www.scaniverse.com).

2.3 Other instumentation used

The TLS Leica RTC360 was used for the reference dataset. With a scanning speed of 2 million points per second and a range of up to 130 meters, it efficiently captures detailed point clouds. The system employs LiDAR and visual SLAM for real-time, targetless field registration, allowing fast data collection. Its HDR imaging system ensures high-quality texture and color capture. The system has three possible resolutions, respectively 3, 6, or 12 mm at 10 meters. Declared precision on 3D points of 1.9 mm at 10 m, 2.9 mm at 20 m, 5.3 mm at 40 m.

3. Data acquisition

3.1 Reference Dataset

To carry out the comparisons, it was essential to identify a survey datum that could be considered accurate, reliable, and as close to reality as possible. For this purpose, the TLS survey data was used. In both the test areas, low-resolution scans were made (i.e. 12 mm at 10 meters for the instrument used). For case study A 24 scans were taken, for case study B 13 scans were taken. The raw data acquired with the TLS was then processed and registered with the Leica Register 360 Plus software. The registration procedure was done by relying on Iterative Closest point (ICP) algorithm, with a statistical final registration error lower than 10 mm in both cases. Point clouds were merged in a unique database and exported in .las format to be used as reference having 215.7 million points for case A and 98.1 million points for case B. The survey and data processing took approximately 60 minutes for each case study.

3.2 iPad apps

The survey with apps was carried out following the instructions in the manuals and user guidelines of the various apps. From reading these suggestions, it was decided to proceed following two different surveying paths. The first path (identified as A1 and B1) was performed by creating a closed loop, i.e. starting and closing the survey in the same position. The second one (identified by A2 and B2), on the other hand, was realized by walking in a zigzag pattern, and then starting from the same starting point and gradually surveying both the right and left sides of the trajectory realized, ending the path at the end of the survey area. The two planned paths were pursued with all five apps and in both case studies, for a total of 10 point clouds to be analyzed for each case study. These paths are exemplified in Figure 1 and 2 together with maps and images of the test areas.

Operatively speaking, since the range of the LiDAR system was 5 meters, we gave priority to surveying the lower parts of the areas studied. Therefore, for the corridor and the rooms (case A), we surveyed the floors, the walls, and only a portion of the vaulted ceilings, because they were quite high, and also because some of the apps'manuals suggested to avoid to survey the ceilings unless strictly necessary. Similarly, for the street (case B), we only surveyed the lower part of the building façades, which obviously had an overall height significantly higher than the range of the instrument used. As previously mentioned, we conducted the survey assuming that only the Apple device was available, so even in the case of the 'Dot3D' and 'RTAB-Map' apps, which allowed for the positioning of targets recognized automatically by the app, these were positioned (and used by the app optimization process), but the targets coordinates deduced from other instruments (e.g. the TLS) were not entered in the app during post-processing of the data.

Each app had different survey settings and options, but we always tried to keep the default options, changing them if necessary in order to use the maximum range for LiDAR and the highest possible resolution. In all the applications tested, what was displayed on the screen was very similar and consisted of the augmented reality view, where the image captured by the camera was displayed in real-time on the screen, superimposed by a grid of points or a mesh (depending on the application used), seen in transparency, which made it possible to understand what has been measured and what has not. In addition, in some cases ('Polycam', '3D Scanner App'), when parts that have already been measured were measured again, it was possible to 'update' the mesh previously constructed. For some applications, some hints appeared on the screen during the acquisition ('Polycam', 'Dot3D'), like 'reduce movement speed', or 'go back'. Furthermore, in the case of 'RTAB-Map' it showed when a 'loop closure' was recognized and the presence of markers in the scene. 'Dot3D' and 'RTAB-Map' also showed when a marker was recognized during acquisition. For some applications, the tutorials suggested preferring a zigzag path for large areas ('Polycam'), for others, it was suggested to create loops ('Dot3D', 'RTAB-Map').

Some apps ('3D Scanner', 'Dot3D', 'Polycam', 'RTAB-Map') allowed to make a survey and append, at a later stage, further surveys to it. Although the possibility of using this method was examined, especially in the case of the corridor (e.g., surveying first the corridor and then appending the rooms), this option was not used as it was more time-consuming and rather cumbersome to execute. Ultimately, it was easier to capture everything in a single acquisition.

App	Cost	Key Capabilities	Ideal Use Cases
3D Scanner App	Free	Simple LiDAR-based 3D scans, object and space capture	General 3D modeling, hobbyist and casual scanning
Dot3D	Free mode with no data sharing or export options. Pro at 49.99 € per month or 349.99 € per year	Detailed 3D capture for architecture and engineering, LiDAR-based precision	Professional-grade architectural scans, industrial use
Polycam	Free basic plan, export capabilities, and other features on Pro version (26.99 € per month or 134.99 € per year)	3D photogrammetry, LiDAR-based scanning, 360-degree capture	Architectural scans, object modeling, real estate
RTAB-Map	Free, based on an open source project	Real-time 3D mapping, loop closure detection, integrates with ROS (Robot Operating System)	Robotics, academic research, environmental mapping
Scaniverse	Free	High-quality object and space scanning, supports LiDAR	Space documentation, AR/VR content creation

Table 1. Features of the app selected for the study presented in this paper. The specifications and features in this table have been compiled from the description of each app in the iOS App Store

3.2.1 Case A: corridor When surveying case A (corridor), in both the case of the closed path (A1) and the case of the zigzag path (A2), the starting point was the final part of the corridor, which was configured with a wall interrupting the corridor itself. In order to survey the spaces then, we always tried to frame elements that had a non-flat geometry, thus framing the edge between the wall and the floor, or framing a door and its edges, or framing the chairs that were present in the corridor. In both cases, A1 and A2, the movement followed with the iPad was a regular movement from bottom to top, held as we walked moving forward in the environment. Then, to move from one space to the other, we surveyed the door from the outside, the right, left, and upper eaves, and their attachment to the ground. Once the door was defined in this way, we moved inside the room, surveying all its parts and surveying moving clockwise until we returned to the door, taking up its eaves and exiting back into the corridor.

In case A1, priority was given to surveying the right-hand side, i.e. we surveyed the floor and walls on the right-hand side with their features, and the rooms (as they were on the right-hand side following the path) until we reached the end of the corridor. When we arrived at the end, we turned around and, again taking over the right side (which was previously on the left) we returned to the starting point. For all apps, when we returned to the starting point, a shift was observed, even a considerable one. In some cases during the processing of the data ('RTAB-Map', 'Dot3D') this shift almost disappeared, in other cases it was only reduced but not canceled ('Polycam', '3DScanner App', 'Scaniverse').

In case A2 we started surveying from the end of the corridor, but instead of starting by surveying only one side, we proceeded to survey both sides at the same time. We moved in a zigzag pattern, i.e. surveying a portion of the right side by moving towards it, then turning to the left side and surveying a portion of it, then moving back to the right, proceeding in this manner until completion. The only interruption to this procedure was followed for the rooms, where we moved in a clockwise manner, but then returning to the corridor we started zigzagging again. Occasionally we re-measured portions already surveyed (i.e. we turned around and re-measured close portions already measured) to try to correct any drifts and deviations that had occurred. In this mode, it was not possible to detect errors or deviations at the end of the survey because there was no overlapping of data.

3.2.2 Case B: street To survey in case B (street) both for the closed path (B1) and the zigzag path (B2), the starting point was at an open doorway. From this position, we then moved on to survey both the street pavement and the façade of the buildings. Obviously, considering that the LiDAR sensor acquisition range is 5 meters, we surveyed as much of the façade as possible. We moved taking care to frame elements with a non-planar geometry during the movement, although in this case the façades and pavement were predominantly flat elements. Two parked cars and closed windows or doors were the only not planar geometries present.

In case B1, we surveyed the facades of the buildings on the right-hand side, standing and walking more or less in the middle of the street (note that the street was rather narrow, with only one lane) and moving the iPad from bottom to top while walking at the same time. At the end of the route, we switched from the façade of one building to that of the building in front, continuing to survey and using only the pavement as the connecting element and thus only framing, in effect, a flat surface. This step may have been critical as it constitutes an element with flat geometry with few constraints. Returning to the starting point, we noticed, as seen above for case A1, a shift between the initial and final point, even a considerable one. In some cases after the processing of the data ('RTAB-Map', 'Dot3D') this shift was practically canceled, in other cases, it was only reduced but not canceled ('Polycam', '3DScanner App', 'Scaniverse').

In case B2, on the other hand, the left and right sides were surveyed simultaneously as we moved from the starting point towards the end. In this way, the initial doorway was surveyed, and then a portion of the wall on the right side was surveyed, then turned with the instrument towards the left side and approached it, and then again on the right side, proceeding in this way to the end. In this case, the floor was often framed, but with each movement, an attempt was also made to survey again (even if only for a few seconds) portions of the buildings surveyed just before, to correct possible drift errors or deviations in the reconstruction. In this case, B2 a critical point was at the turn of the corner where several times only the floor was surveyed for several seconds, which could have been a source of drift in the reconstruction. As for case A2, it was not possible to detect errors or deviations at the end of the survey because there was no overlapping of data.

3.3 Apps data processing and export

The processing of the acquired data was carried out directly on the iPad within each app. The various apps offer different settings. When possible, processing that implied fewer simplifications and produced denser data was chosen and prioritized. In all cases, the processing phase took less than 10 minutes to complete. Then, considering data export, apps allowed various export formats including textured mesh models and point clouds, but to have consistency with the data from all tools, it was decided to export only point cloud files. The only app for which post-processing with computer software was carried out was 'RTAB-MAP'; this was necessary as the scan files were too big and it was not possible to export the point clouds directly on board the app, but only the raw database. With the RTAB software (which is open-source and downloadable from www.introlab.github.io/rtabmap), it was possible to carry out post-processing and export of the cloud. In the following, there is a more complete description of the processing and export options available from the various apps, with a description of those chosen and used.

'3D Scanner App' allows the use of processing pre-sets, or also allows customisation of smoothing (0 to 8x) and simplification (0 to 95%) options. We chose to process the data with 0 simplification and 0 smoothing. If the use of GPS has been enabled among the acquisition options, the resulting model is also georeferenced. Export formats are usdz, web link, video, floorplan image, obj, gltf, glb, stl, pcd, ply, pts, XYZ, las, e57, sketchfab, dae, prd.in, fbx.

'Dot3D' allows the user to set the maximum LiDAR acquisition depth from 0 to 5m, to choose whether to automatically detect AprilTags or not, to set the units in the metric system or in the US system, plus other specific settings related to the use of the device's ARkit to improve the pose during acquisition. Post-survey optimization options include the use of ARkit or not to search for additional constraints (i.e.: full, position-only, none), the use of AprilTags in the reconstruction and the use of any manually annotated points as constraints. It is also possible to enter the coordinates of AprilTags or manually annotated points. We have used both AprilTags and a 'full' use of constraints with ARkit, without entering AprilTag coordinates. Export formats are dp, e57, las, laz, pts, ptx, ptg, ply, rcs, pod.

'Polycam' allows the data to be processed following some presets adapted to the size and type of object detected (rapid, space, object), or allows customization options, choosing the depth range (from 0.1 to 6 m), the size of the reconstructed voxel (from 36 to 100 mm), the percentage of simplification of the data (from 0 to 99%), whether to use an automatic crop or not, whether to calculate considering a closed loop or not. The GPS data, if selected in acquisition options, is saved. We used the maximum depth range, minimum voxel size, no simplification, no crop, loop closure depending on how the survey was done (in cases A1 and B1 yes, in cases A2 and B2 no). Export formats are obj, gltf, fbx, dae, stl, usdz, ply, las, geolas (only enterprise), pts, xyz, dxf, blueprint, and images.

'RTAB-Map' allows many parameters to be set, both related to data acquisition and processing as well as to trajectory reconstruction and loop closures, and related to mapping and assembling. These include point cloud density (maximum, high, low, very low), maximum LiDAR acquisition depth (1 to 5 m), minimum depth (0 to 3 m), mesh reconstruction settings including triangle size (2 to 6 px), decimation (0 to 99%), texture resolution (maximum, high, low, very low). The app also recognises various markers including AprilTag and ArUco. It also allows to use GPS data in reconstruction. We used a maximum point cloud density, with an acquisition depth of 0 to 5 meters, minimum triangle size, and no decimation, with texture at maximum resolution. The export formats are db, ply, obj. For the surveys performed in this test, it was not possible to export the data from the app in ply or obj format, but only in .db format, which exports the raw data and is readable by the open-source software RTAB. Post-processing was therefore performed in this software, using the default settings and only modifying the settings related to loop closure search, increasing its sensitivity. We therefore set 8 metres as the cluster radius and 20 iterations. At the end of the processing, the point clouds were exported in ply format.

'Scaniverse' allows three predefined processing options: speed mode, area mode, and detail mode. Speed mode is the fastest, uses LiDAR data with 120 mm resolution, and is the one that uses the lowest resolution. Area mode is ideal for rooms and spaces, uses LiDAR with 40mm resolution, reconstructs the scene using LiDAR on devices with LiDAR sensor and neural networks on devices without one. Detail mode can only be used for short-duration surveys and is recommended for small objects, it reconstructs the scene using only photogrammetry. The app allows the use of GPS data, especially for sharing models also online with the community. We used area mode. Export options are fbx, obj, glb, usdz, stl, ply, las, video, web link, sketchfab ready.

4. Data analysis

All point clouds exported from the previous step were imported into CloudCompare (CloudCompare, 2024c) for analysis. To make appropriate comparisons, the TLS dataset was used as a reference. Each point cloud was then first manually placed close to the TLS point cloud, and then using the 'Fine registration (ICP)' command it was finely registered on the laser scanner point cloud. To do this, an RMS of 1.0E-05 and overlapping of 70% (to take into account any unsurveyed portions in both point clouds) were used in the calculation options. After the fine alignment was completed, the point clouds were compared to each other and to the TLS one using various methods and approaches.

4.1 Visual inspection

The first analysis consisted of a visual evaluation: density of points on surfaces, attributes present in the point cloud, and eventual macro deformations clearly visible and evident. For the point density, the geometric feature 'Surface Density' CloudCompare (2024b) which is available under "Tools - Other - Compute geometric features" was used. It provides information on the average number of points per square meter on each surface in the point cloud.

It was observed that point clouds from different apps had different values in terms of the point density on the surfaces and thus in the overall number of points. This also depended on the options selected during post-processing on each app. Concerning the total number of points, 'Dot3D' was the app that had values one order of magnitude higher than the other apps (i.e. 100 million points). Of the other apps, two groups could be identified, respectively an order of magnitude of 10 million ('3D Scanner App', 'RTAB-Map') and 1 million or less ('Scaniverse', 'Polycam'). It was unknown and not controllable whether this

Number of points (millions)				
App	**A1**	**A2**	**B1**	**B2**
3DScanner App	26.20	8.82	11.21	11.15
Dot3D	191.00	200.80	133.13	119.61
Polycam	0.55	2.78	1.09	1.50
RTAB-Map	20.70	15.56	13.01	10.79
Scaniverse	0.86	0.71	0.59	0.88
Leica RTC-360	215.69		98.09	
Surface Density (thousands of pts per square meter)				
App	**A1**	**A2**	**B1**	**B2**
3DScanner App	27.80	10.14	10.08	9.89
Dot3D	368.87	310.57	197.51	147.79
Polycam	0.48	2.52	0.83	1.29
RTAB-Map	22.08	19.50	13.33	13.79
Scaniverse	0.84	0.84	0.44	0.83
Leica RTC-360	179.88		29.68	

Table 2. Number of points expressed in millions and average values of Surface Density expressed in thousands of points per square meters for point clouds acquired by each app for case study A and B using a loop survey path (A1, B1) and a zigzag survey path (A2, B2). TLS data are present in the last row as reference for cases A and B.

result was produced solely from the LiDAR data or whether it was done through a photogrammetric process generated from the photographs or the textured mesh. However, it could be noted that 'Dot3D', which produced very dense point clouds, exhibits the Intensity attribute, which is intrinsically linked to the LiDAR data. All point clouds from the other apps only had the xyz coordinates of the point and the RGB color as attributes. The total number of points in each point cloud, regarding all the paths and all case studies are shown in Table 2. The table also shows the values for the TLS data as a comparison parameter.

For the point density feature, there was a predictable lowering of the density as moving upward in elevation, in fact for vertical surfaces the higher their elevation and further away they were from the scanning instrument. Furthermore, it was observed that the density of points in the case of the loop (A1 and B1) was in general higher than that in the case of the zigzag path (A2, B2), but this could be also related to how the survey was conducted. In fact, in the case of the closed loop path, some elements were detected more than one time. Surface density values, reported by Table 2, reflect quite well what has already been observed for the total number of points in each point cloud, with the 'Dot3D' app producing point clouds with surface densities even higher than those in the TLS point cloud.

Visible macro-deformations were qualitatively identified by visual comparison with the TLS point cloud. They were much more evident when the use of the app was done following a path that was not appropriate for the app itself. In other words, very evident deformations, such as trajectory drift errors and macro deformations of the overall point cloud were found with the 'Polycam', 'Scaniverse' and '3DScanner App' apps when used with a loop path instead of a zigzag path. By contrast, with 'RTAB-Map' and 'Dot3D' the deformations were higher when a zigzag path was used, even if not of the same magnitude as those previously observed, but much smaller and in some cases even difficult to perceive without a large zoom.

4.2 Analytical comparison

The second analysis consisted of a comparison between the TLS point cloud and each point cloud acquired by the apps. This comparison was made by using the CloudCompare tool 'Cloud to Cloud (C2C) distance calculation' CloudCompare (2024a) to identify the areas with the greatest deviation from TLS data, and also by observing the distance values in the histogram, in which the statistical distribution of point distances was shown. In addition, by making slices on the horizontal plane, the positions of characteristic architectural points (e.g., wall corners) were compared to identify any drifts or deviations between the analyzed datasets.

Regarding the direct comparison between each point cloud and the TLS point cloud with the C2C method, the results were graphed in the form of Gauss curves. In those diagrams, the frequency exhibited by a given distance value between the analyzed point cloud (which changes for each curve) and the reference point cloud (always TLS) was displayed.

For the test area A (Figure 3), it was observed that the best results, statistically speaking, were obtained with 'Dot3D' and 'RTAB-Map' in the closed loop path case and with 'Scaniverse' in the zigzag path case. With these 3 cases, curves with low mean values (0.04, 0.05, 0.07 m respectively) and low standard deviation (0.04, 0.05, 0.06 m respectively) were observed. In all other cases, much higher means and standard deviations were observed, which were not comparable with the 3 previously mentioned.

In the case of test area B, (Figure 4), the best results were observed for 'Polycam' in the zigzag path case and 'Dot3D' in both the closed loop path and zigzag path case, followed closely by RTAB-Map in the closed loop path case. The mean values of these cases ranged from 0.04 m to 0.07 m, with standard deviations from 0.05 m to 0.08 m. The other applications had much higher values.

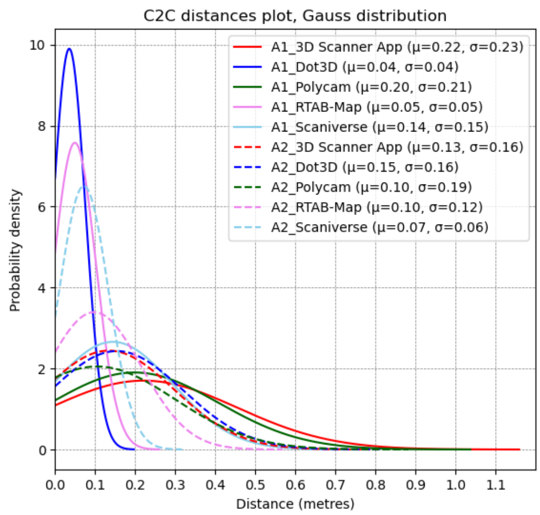

Figure 3. Gauss distribution curves for the C2C distances computed between each point cloud and the TLS point cloud. Graph legend reports also mean value (μ) and standard deviation (σ) of each plot. Plots refer to test area A (corridor), with a closed loop (A1) or zigzag (A2) survey path.

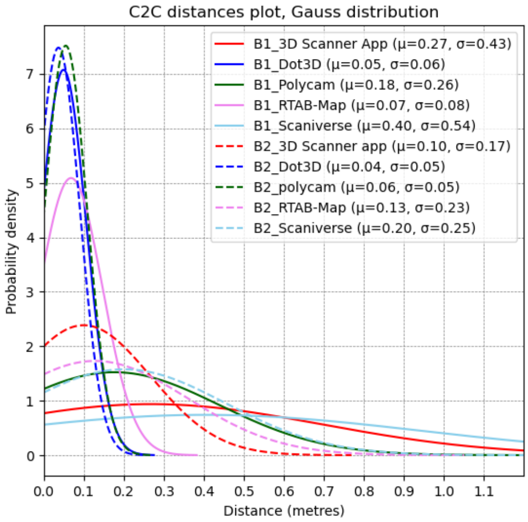

Figure 4. Gauss distribution curves for the C2C distances computed between each point cloud and the TLS point cloud. Graph legend reports also mean value (μ) and standard deviation (σ) of each plot. Plots refer to test area B (road), with a closed loop (B1) or zigzag (B2) survey path.

The graphs we analyzed showed global information about deviations between the point clouds obtained with the various apps and the TLS dataset. It could be interesting to also observe the extent of the deviations locally. To this end, a slice in the horizontal plane was performed on each dataset and the deviations of notable points, such as angles between walls and door squares, were observed (Figures 5 and 6). To do this analysis, only the point cloud made with the survey approach (i.e., path) that produced the best statistical result in the previous analysis was used for each app; this information can be seen in the legend of the Figures.

What was observed, in both test areas, was that locally there were much greater deviations from the statistical mean value, for each app it was up to 4 times the mean value of the same app in the C2C calculation. Furthermore, it was noted that in some places the point clouds were very similar and well adherent to the TLS data (case 2 of Figure 5 and case 3 and 4 of Figure 6), in other cases all showed a greater deviation (case 1 of Figure 5 and case 1 of Figure 6), in other cases some were more adherent and others clearly with out-of-scale and much greater errors (case 3 and 4 of Figure 5 and case 2 of Figure 6).

5. Discussion and Conclusions

This study analyzed the effectiveness of various surveying applications utilizing the LiDAR sensor on iOS devices. We selected five apps and tested them on two medium-sized case study areas, one indoor (a corridor with rooms) and one outdoor (a street segment). Surveys followed either a closed-loop path or an open, zigzag path.

The analyses revealed that certain apps produced results with lower statistical deviations from the reference dataset, which was generated using TLS. Specifically, 'Dot3D' among the paid applications and 'RTAB-Map' among the free ones showed the smallest deviations, both in statistical measures and in local

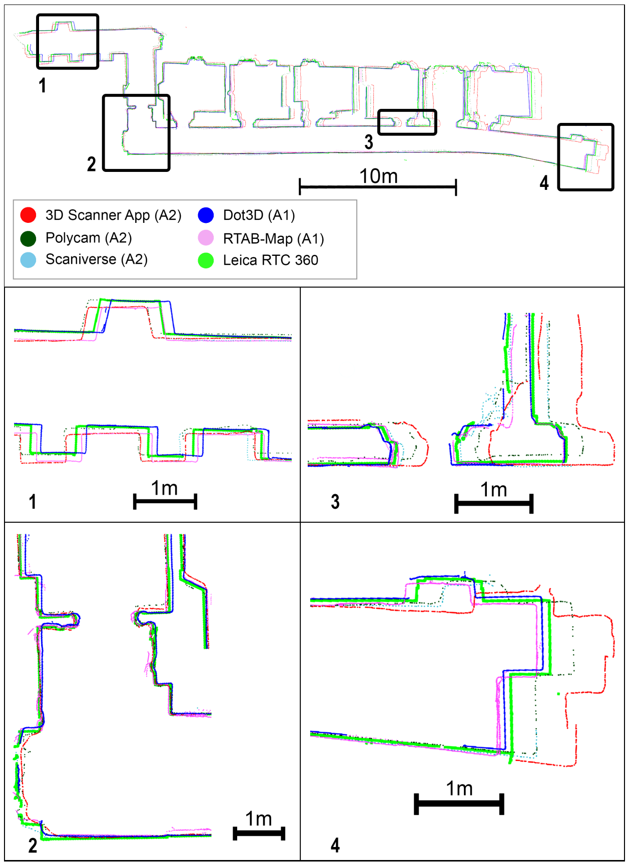

Figure 5. Analysis of local deviations between the various point clouds with reference to the TLS point cloud in the case of the corridor (test A).

point cloud accuracy, as observed through cross-sectional slices. 'Dot3D' appears to be optimized for professional and commercial use, while 'RTAB-Map,' available at no cost, seems more suited to research purposes.

Interestingly, both 'Dot3D' and 'RTAB-Map' performed best when used with a closed-loop survey path, in particular when markers were detected. This suggests that, for medium-sized survey areas, applications that employ loop closure algorithms with marker assistance tend to produce more accurate results. Other apps ('3D Scanner App,' 'Polycam,' and 'Scaniverse') produced better results with zigzag paths, albeit with higher error margins. Generally, errors ranged from a few centimeters to several tens of centimeters, including local deviations. What emerged was that each application processed the data differently and produced very different results, depending also on the survey path used. It might be interesting in the future to better investigate how the survey path used is correlated with the calculation algorithms used by the various apps to define the ideal approach in these cases. Then, it is also important to consider that, although many applications utilize the LiDAR sensor, other alternatives not evaluated in this study may potentially yield even more accurate results.

From an operational perspective, both the data collection and processing phases were relatively quick, typically completed within 20 minutes, although some variation occurred depending on the specific application and survey conditions. This efficiency suggests the potential for rapid surveys, albeit with error margins in the range of several centimeters. Notably, the

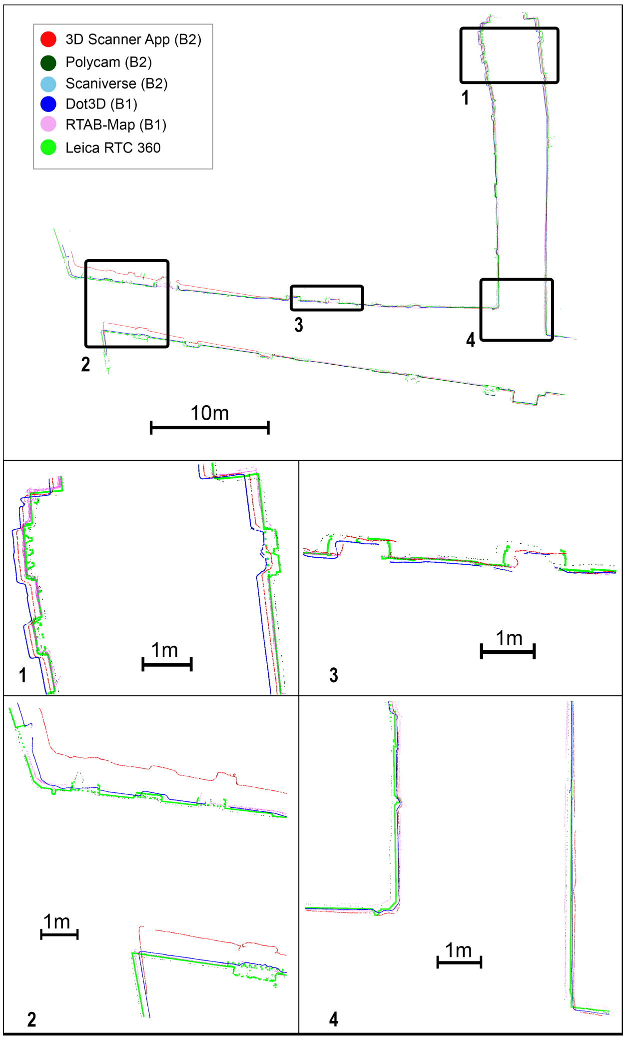

Figure 6. Analysis of local deviations between the various point clouds with reference to the TLS point cloud in the case of the road (test B).

most significant deviations were found in areas with curved or predominantly flat geometries, suggesting that such features should be surveyed carefully, ideally with additional markers when possible. Although a multi-stage survey approach was considered, it was not tested in this study.

The findings indicate that Apple device's LiDAR survey system has potential applications in outdoor environments, such as urban and road management, for quickly identifying localized issues requiring documentation. For indoor environments, the system also shows promise; however, it would be beneficial to investigate further the feasibility of appending new scans to previously surveyed data, allowing complex areas to be surveyed incrementally in smaller, controlled stages. Additional precautions should be taken in areas with curves or abrupt directional changes, particularly in flat geometric regions, to mitigate errors.

Future research directions will focus on enhancing the use of the point clouds generated with this method. This includes investigating semantic segmentation, making the data accessible through web platforms or virtual reality, and exploring the potential for graphic representation of the surveyed elements, such as through vectorization and GIS or BIM integration.

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