3D MAPPING OF INDOOR AND OUTDOOR ENVIRONMENTS USING APPLE SMART DEVICES

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ABSTRACT:

Recent integration of LiDAR into smartphones opens up a whole new world of possibilities for 3D indoor/outdoor mapping. Although these new systems offer an unprecedent opportunity for the democratization in the use of scanning technology, data quality is lower than data captured from high-end LiDAR sensors. This paper is focused on discussing the capability of recent Apple smart devices for applications related with 3D mapping of indoor and outdoor environments. Indoor scenes are evaluated from a reconstruction perspective, and three geometric aspects (*local precision*, *global correctness*, and *surface coverage*) are considered using data captured in two adjacent rooms. Outdoor environments are analysed from a mobility point of view, and elements defining the physical accessibility in building entrances are considered for evaluation.

1. INTRODUCTION

Over the last few decades, scanning technology has undergone a considerable reduction in price and diversification of devices: from expensive laser scanners mounted on tripods, to backpack systems, to handheld devices and finally to integration into smartphones. Examples of the latter are the new iPhone 12 Pro and iPad Pro launched by Apple in 2020 (Apple, 2020).

Given that the number of global smartphone users is estimated into 3.8 billion for 2020, and it is expected to grow by several hundred million in the next few years (Bankmycell, 2021), integration of scanning technology into smartphones offers new opportunities related to accessibility, versatility, and connectivity. By contrast, the technical quality is lower than in specific devices (Abdelhamed et al., 2018; Zhu et al., 2020), and in most cases, acquisitions are made by inexperienced users (Fang et al., 2020), which implies a further deterioration of data quality.

According to the manufacturer, Apple has promoted and justified the installation of LiDAR in iPhone 12 Pro and iPad Pro as improving the camera's properties while enabling 3D data acquisition (Apple, 2020). The new integrated technology increases accuracy and speed of focusing, especially in low light conditions. Regarding 3D data acquisition, through different apps, the LiDAR allows taking measurements, generating point clouds or meshes, and the data integration in Virtual Reality (VR) or Augmented Reality (AR) environments. However, the manufacturer does not provide a datasheet on the technical specifications of the LiDAR, which means that consumers do not know the real applicability of the device in situations highly dependent on precision and accuracy.

The integration of scanning features into mobile devices opens up a whole new world of possibilities for 3D indoor/outdoor mapping and the use of AR. Data acquisition is much faster than with a static Terrestrial Laser Scanning (TLS) device, in addition to the savings in post-processing (data registration) time. During acquisition, the point cloud or mesh of the data being acquired can be displayed in real time on the image of the environment (Hübner et al., 2019; Khoshelham et al., 2019). It is also possible to visualise proposed changes to the built environment, detect deviations, positioning objects and removing/adding structural elements (Chalhoub et al., 2021; Koutitas et al., 2020; Nagao et al., 2019; Zhang et al., 2020). Another application of great interest is indoor positioning, guidance and navigation using 3D data and AR (Gerstweiler, 2018; Li et al., 2020; Mahmood et al., 2020; Ng and Lim, 2020).

This paper will discuss the new opportunities of Apple smart devices such as iPhone 12 Pro and iPad Pro for indoor/outdoor modelling. Given the reduced range of these systems, outdoor modelling will be discussed from a mobility point of view. A comparative geometric evaluation following the method implemented in (Khoshelham et al, 2019) will also be performed with equivalent data acquired with a Terrestrial Laser Scanner.

2. THE SYSTEM

Because the technical specifications of the scanning system of iPhone 12 Pro and iPad Pro are not available, a few works evaluating the measurement capabilities of these systems have been recently published.

In (Vogt et al., 2021), a measurement evaluation was conducted by positioning the sensor at a distance of 300 mm and at an angle of 65º. From the tests carried out, the authors concluded that the scanning technology of the iPad Pro is proved to be impractical for scanning small objects such as Lego bricks. For this reason, no results could be obtained to determine data accuracy. The average deviation was 0.16 mm in the Lego bricks.

In (Spreafico et al., 2021), an outdoor emergency stair was acquired with the iPad Pro to evaluate the quality of the acquisitions. The iPad Pro was tested in a static configuration mounted on a tripod and in a manual dynamic configuration.

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The authors concluded that the points, measured by the topographic method with the iPad Pro were suitable for 1:200 map scale. The iPad Pro scans were characterised by a Root Mean Square Error (RMSE) mean value lower than 2 cm and a standard deviation lower than 1 cm, and scans from the Faro Focus X330 TLS data were a RMSE mean value lower than 3 mm and a standard deviation lower than 1 mm. The iPad Pro has a resolution between 500 up to 16000 points, producing point clouds with fewer points than TLS and smaller file weight.

(Murtiyoso et al., 2021) evaluated the quality and usability of the iPad Pro from a Solid-State LiDAR (SSL) perspective. The authors compared the results of acquisitions using SSL versus TLS and photogrammetry to obtain point clouds. Although the acquisition and processing time is shorter and the geometric quality is promising, according to the authors the amount of noise does not yet allow for high-precision applications, although these point clouds are very useful for visualisation. Also, ambient light is another limitation as the system is based on RGB colour for tracking. The authors recommended to use static acquisitions in difficult scenarios and reduce the point density resolution in the acquisition. SSL technology also has the same limitation to acquired reflective surfaces as conventional LiDAR.

Apple iPad Pro has also been evaluated for forest inventory by means of the measurement of parameters such as tree position and diameter at a breast height (dbh) (Gollob et al, 2021). Results showed a detection rate higher than 97% and a RMSE in dbh around 3 cm. Therefore, these affordable and cost-effective systems were concluded to be feasible for forest inventory, obtaining an admissible accuracy and precision in comparison with traditional approaches.

Topographic surveying in earth sciences has also recently been evaluated using iPhone 12 Pro (Luetzenburg et al, 2021) compared with a Structure from Motion Multi-View Stereo (SfM MVS) point cloud. Results show that the precision is decreasing for objects with a side length lower than 10 cm, but reliable results are obtained for objects above that threshold with an absolute accuracy of ± 1 cm in comparison with smartphone photogrammetry.

In this work, a small (24.76 x 17.85 cm^2) and lightweight (466 g) iPad Pro (4th generation) is the device used for data acquisition. Although the type of sensor remains a trade secret, some studies define it as a solid-state LiDAR (Murtiyoso et al, 2020), which is a Time-of-Flight LiDAR without requiring mechanically moving parts. The sensor creates a fine grid of points, with the distance to each point measured individually (Spreafico et al, 2021). The maximum range is stated in 5 meters, and point density follows a linear trend potential point density follows a linear trend on a logarithmic scale with 7,225 points at 25 cm distance and 150 points at 250 cm distance (Luetzenburg et al, 2021).

Although there are still a limited number of applications for surveying with Apple devices, the number is growing. In this paper, *3D Scanner* (Laan, 2021) is the application used to test the survey capabilities of the iPad Pro. It is free and supports obj, gltf, glb, dae, stl, pts, pcd, ply and xyz data formats. The software allows low- and high-resolution capture and real-time display (Figure 1).

Figure 1: View of the data capture process.

3. METHOD

As previously mentioned, the paper is focused on evaluating the mapping capabilities of Apple smart devices for indoor and outdoor environments. In terms of indoors, the evaluation of data quality is focused on three main geometric aspects: *local precision*, *global correctness*, and *surface coverage* (Khoshelham et al, 2019).

Local precision gives an idea about the precision of individual points captured by Apple smart devices. *Local precision* is measured as the RMSE of point distances to fitted planes on planar surfaces.

Global correctness describes to what degree the global shape of the scene is consistent with the actual layout and dimensions. *Global correctness* is measured by double comparison with i) reference data captured with a TLS and ii) with reference 3D model of the building. For comparison with *reference data*, we use data captured with the Faro Focus x330 system (Khoshelham et al, 2019, Spreafico et al, 2021). Data captured by the Apple smart device is registered with data captured with the Faro Focus x330. Then, the comparison is performed by computing distances between Apple point cloud and the closest point into the TLS point cloud. As in (Lehtola et al., 2017) and in (Khoshelham et al., 2019), a cut-off distance is applied to reduce the influence of gaps and coverage discrepancies between the two datasets. For comparison with *reference 3D model*, we apply the method implemented in (Tran et al, 2019) based on analysing point-model distances. For this purpose, a 3D BIM model is manually created from the reference data. Distances between the point cloud and the closest surface in the 3D model are computed considering a certain cut-off value.

Surface coverage measures to which extent a surface has been captured. For this purpose, points are orthogonally projected on the corresponding surface to construct a 2D alpha-shape. *Surface coverage*, introduced by (Tran & Khoshelham, 2019), is measured as the ratio of the area of the alpha-shape to the area of the reference surface.

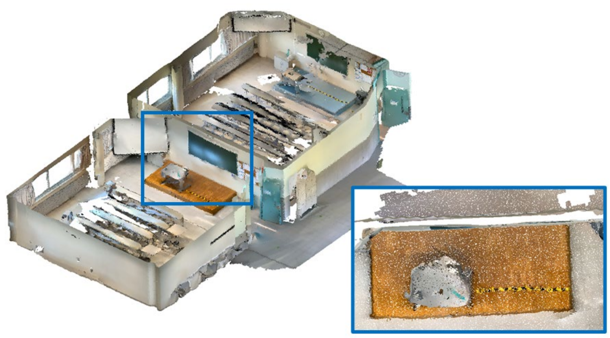

Figure 2: The indoor scene composed of two consecutive rooms scanned with iPad Pro, and a zoom from a top view.

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An indoor environment composed of two adjacent rooms is used as case study for indoor mapping performance analysis. Figure 2 shows a general view of the scene in which the ceiling has been removed to give a better visualization of the interior, and a zoom in from a top view to see how an intermediate wall is captured from both sides.

For outdoor mapping, one of the main restrictions of these LiDAR integrated smartphones is the reduced range of acquisition, which is stated in 5 meters. Consequently, the interest of these new consumer-grade devices is not in the massive capture of the outdoor environment but in areas of difficult access or typically occluded when using car-based mobile mapping scanners. This is the case of areas of high interest in the case of mobility applications for disabled people such as sidewalks and building entrances (Figure 3 and 4).

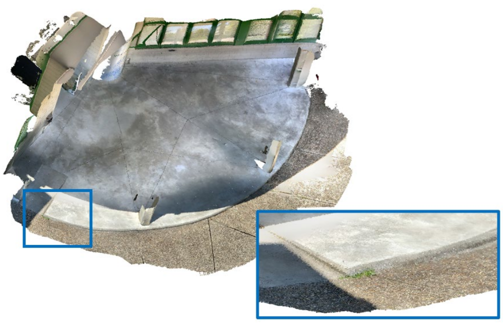

Figure 3: An outdoor scene corresponding to a building entrance, including a zoom in to a ramp.

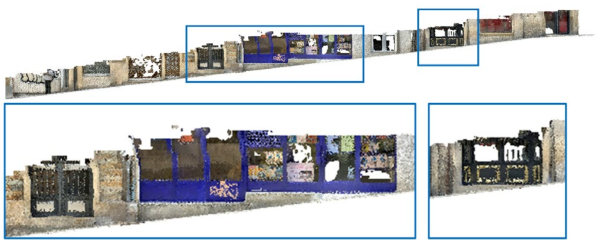

Figure 4: An outdoor scene corresponding to the indoor/outdoor interface of a sloped street.

Urban ground is mostly composed of planar elements such as sidewalks, steps, or ramps. If we consider a low-cost system useful for assisting navigation for physically disabled people, data quality should be high enough to detect barriers to navigation such as steps for wheelchair people. In order to gain an insight whether the data meets this requirement, several tests were carried out. First, *local precision* is analysed in case study 2 (Figure 3). Then, an initial analysis of physical accessibility diagnosis in building entrances (Balado, et al, 2017) is performed from the outdoor scene shown in Figure 4. In the latter experiment, the iPad point cloud is submitted to a geometric segmentation and classification in *horizontal* (blue), *vertical* (magenta) and *tilted* (orange) classes. Because the street is highly sloped, an approximated trajectory followed by the user during acquisition is simulated and a bidirectional classification is implemented to differentiate the tilt in the trajectory direction and the perpendicular tilt to the trajectory direction.

4. EXPERIMENTS AND RESULTS

4.1. Indoor mapping

Indoor mapping capabilities of Apple Smart devices are evaluated from a geometrical point of view. Figure 5 shows the results of *local precision* for data captured by the iPad Pro in the case study depicted in Figure 2. A total of 6 planar segments across the case study have been selected for plane fitting. The local precision measured as the overall plane fitting RMSE over 737008 points on 6 planar segments was 0.53 cm, while 0.28 cm was obtained for the equivalent segments in the TLS data.

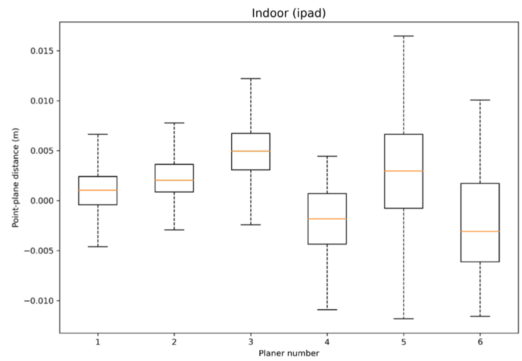

Figure 5. Distribution of point-plane distances for the 6 planes tested from the iPad Pro point cloud.

For evaluating *global correctness*, iPad data is registered with reference data from TLS and with 3D reference model. The 3D reference model (Figure 6) has been manually created in Revit software and registration is performed in CloudCompare.

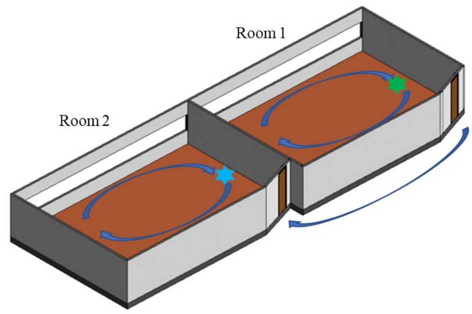

Figure 6. 3D reference model created in Revit software. The ceiling has been removed for visibility purposes. Acquisition trajectory starts in the green star finishing in the blue star.

Figure 7 shows the results of closest point distances between iPad Pro and TLS point clouds. Although a large area is covered by iPad Pro points at less than 10 cm away from the TLS points, parts of ceiling and a wall have much larger distances. In the case of the ceiling, these areas correspond to areas not covered by iPad Pro during the acquisition because the data capture was performed to focus mainly on walls. In case of the wall, the large distances may be due to the SLAM algorithm on iPad. It should be noted that the capture started by Room 1, continued by the corridor, and finished in Room 2 (Figure 6), creating a loop per room with the aim of capturing the room completely but not closing the loop at the global level. Consequently, Room 2 has higher dimensional errors than Room 1 (Figure 11).

Figure 8 shows the result of analysing closest point distances between iPad Pro and BIM model. In terms of structural elements, most of errors correspond to walls belonging to Room 2. Other elements such as pieces of furniture and columns are highlighted in red because they are not in the BIM model.

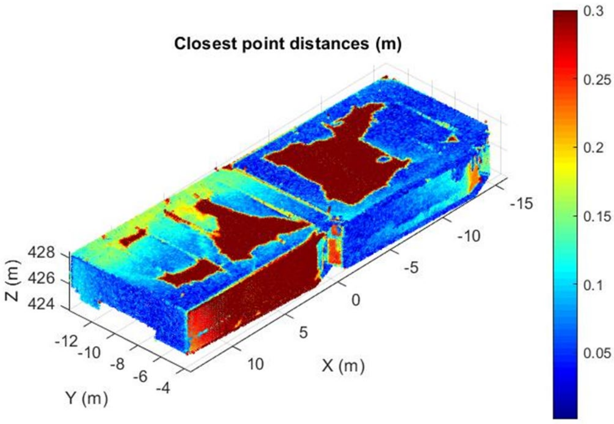

Figure 7. Closest point distances between the iPad Pro and the TLS point cloud.

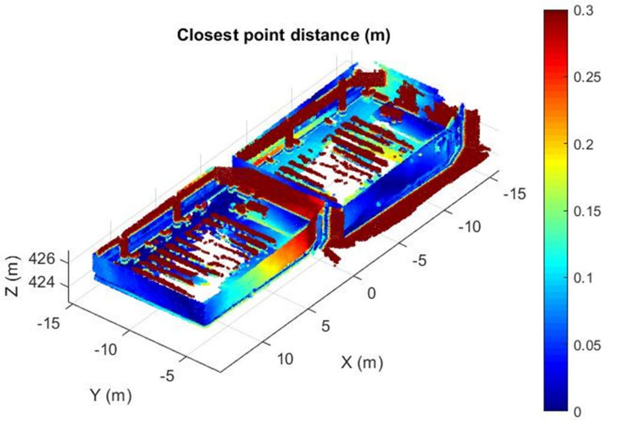

Figure 8. Closest point distances between the iPad Pro and the 3D model. The ceiling has been deleted for improving indoor visualization.

Figures 9 and 10 show the results of *surface coverage*, measuring to which extent each triangular surface has been captured by the sensor. The analysis has been performed considering 10 cm of buffer size. This explains why some interior surfaces captured with iPad Pro and belonging to Room 2 have a coverage close to 0. It should be noted that all exterior surfaces have a null coverage, and this is because they were not scanned.

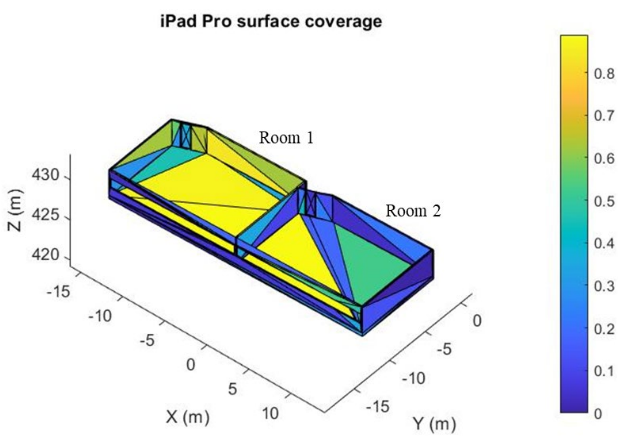

Figure 9. Coverage of the surfaces by iPad Pro.

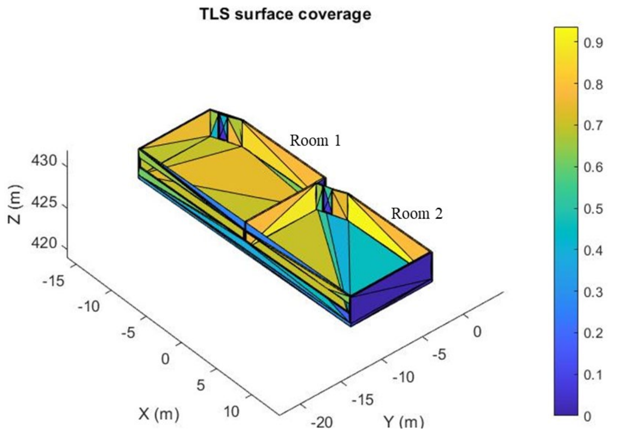

Figure 10. Coverage of the surfaces by TLS.

A top view of iPad Pro and TLS point clouds after registration is shown in Figure 11. As previously mentioned, data capture with iPad Pro started in Room 1 and finished in Room 2. Figure 11 shows that Room 1 preserves quite well the dimensions, and well as the parallelism and perpendicularity between walls. However, data quality in Room 2 may be affected by errors in the trajectory reconstruction, and this is evidenced by the deviations in some walls. Specifically, the wall between Room 1 and Room 2 has 10 cm thickness, while in the data captured by the iPad Pro both surfaces are around 40 cm away. This explains the results obtained in Figure 9 and Figure 11.

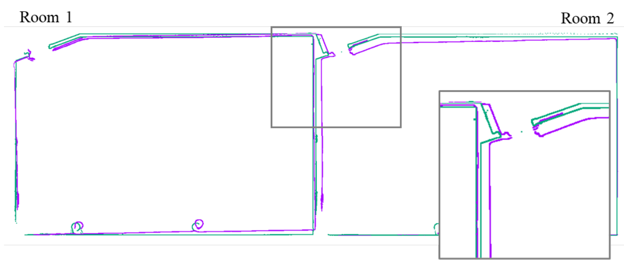

Figure 11. iPad point cloud (violet) and TLS point cloud (green) registered. Ceiling, floor and furniture have been deleted for visualization.

4.2. Outdoor mapping

In terms of local precision, the results are similar to indoor mapping. The local precision measured from fitting 5 planar segments (136863 points), extracted from the case study represented in Figure 3, was 0.56 cm, while 0.17 cm was obtained for the equivalent segments in the TLS data (Figure 12).

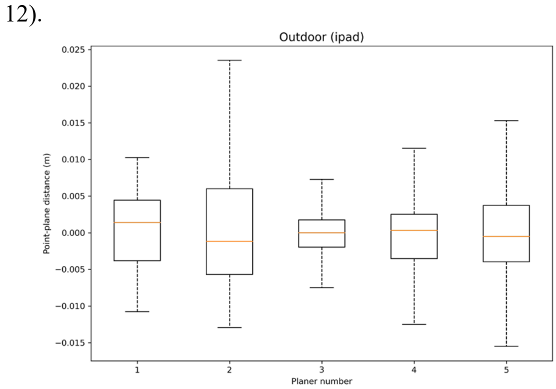

Figure 12. Distribution of point-plane distances for the 5 planes tested from the iPad Pro point cloud

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The physical accessibility diagnosis is just designed for detecting *horizontal*, *vertical*, and *tilted* ground areas. For that purpose a neighbourhood of 50 points is considered for calculating curvature, and just tilted areas with an angle between 5º and 20º, and with perpendicular tilt to the trajectory direction are represented. Figure 13 shows some results obtained from implementing the method into the case study introduced in Figure 4. In Figure 13.a) the ramp is correctly classified as a tilted area, while in Figures 13.b and 13.c, just the area closes to the ground are detected as tilted. Vertical areas are also well identified while more tests would be required to refine the results and to detect which tilted surfaces are truly ramps, and which ones are steps.

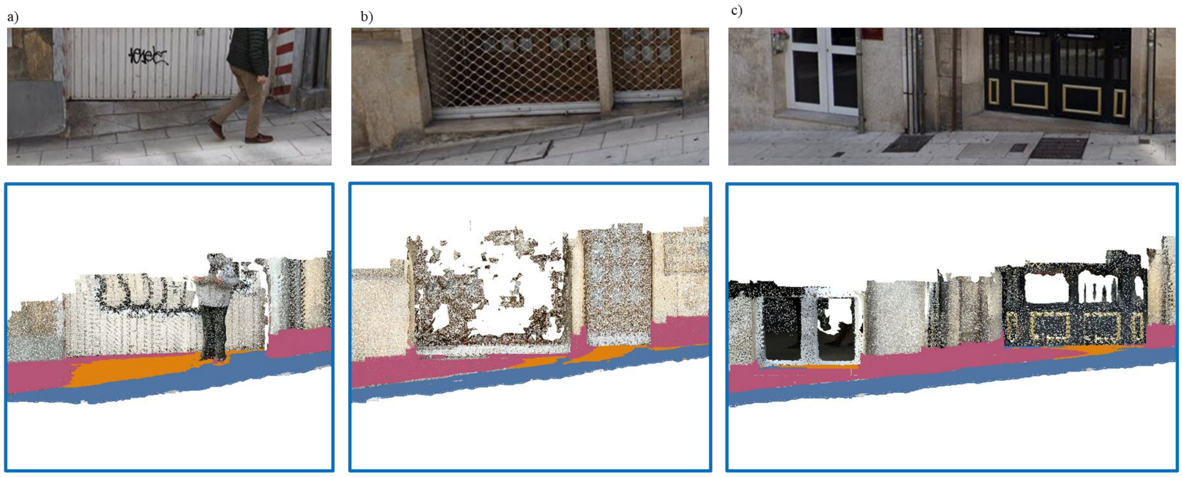

Figure 13. The interface indoor/outdoor of a sloped street captured with iPad is classified into horizontal (blue), vertical (magenta) and tilted (orange).

5. CONCLUSIONS

This paper explores the application of the new LiDAR equipped smartphones for the 3D mapping of indoor and outdoor environments. As it was demonstrated in literature, the new Apple iPad and iPhone Pro devices have their primary field of application in the small to medium scale, being impractical for small-scale objects.

In terms of indoor mapping, a scene composed of two consecutive rooms, with an area around 200 m^2, was captured to be evaluated from the perspective of a 3D reconstruction application. In spite of the fact that several attempts were carried out for capturing more than two consecutive rooms, the generated point clouds were clearly incorrect for more than two rooms (visually, walls were not perpendicular, and they were represented by partially overlapped surfaces). Consequently, only the two-room scene was selected for further analysis. This indicates that the device is only suitable for mapping small environments.

Local precision was analysed on 6 planar segments extracted from walls (7.10^5 points) and resulted into 5.3 mm, being this a very good value for representing planar surfaces in the architectural field. *Global correctness* was evaluated from comparison with TLS data and a BIM model. Most of iPad points were less than 10 cm far away from TLS points and BIM surfaces, while parts of the ceiling and a wall have much larger distances. In case of the wall, the large distances may be due to the process of point cloud creation within the iPad, resulting in larger dimensional errors in the room captured towards the end. In the case of the ceiling, these errors correspond to areas not captured by the iPad. Because the system was manually oriented towards capturing the walls as complete as possible, and the maximum acquisition range is set into just 5 m, the ceiling was not completely acquired. Because a 10 cm buffer was considered, *surface coverage* provides values close to zero in those walls corresponding to the room captured towards the end. This is coherent with previous analyses. Therefore, although the system can be used for 3D mapping of indoors towards 3D reconstruction, special attention should be put into the acquisition planning in order to avoid large and complex trajectories. From the visualization of the data, good colour registration is observed.

In comparison with RGB-D sensors, these new systems are not affected by lighting conditions, so outdoor applications are possible with these devices. In terms of outdoor mapping, an outdoor scene consisting of the indoor/outdoor interface of a sloped street was considered for analysis. Because the limited range of acquisition, these new systems could be highly usable for capturing the navigable urban space for pedestrians, commonly occluded when surveying with car-based mounted MLS given the existence of parked cars. In this context, we explore their use for the detection of urban architectural barriers, hampering mobility specially for people with physical disabilities including people on wheelchairs or elderlies. These LiDAR-equipped devices have initially shown to be useful for detecting *horizontal*, *vertical*, and *tilted* ground elements, although more tests would be required to analyse to which extent they are useful to accurate detect the geometry of normalized ramps and steps. This application would be of maximum interest if point cloud would be processed in real time. Comparison with TLS and BIM reference models would be also interesting for future work. This application would be of a high interest in case of real time processing, constituting an accessible and affordable system for assisting mobility, especially in terms of people with physical disabilities.

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