Low-Cost Geomatics Surveys for Emergency Interventions on Cultural Heritage. The Case of Historic Wall in Cagliari

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Abstract. The documentation and metric knowledge of cultural heritage is becoming an increasingly important need, especially concerning the state of degradation of some historical assets. In this context, the metric documentation of the investigated heritage becomes fundamental for a complete knowledge of the asset to support architects and engineers in the restoration process. Recently, methods and geomatics instrumentation have been developed for the survey of cultural heritage aiming at optimizing costs and time. For example, the Apple has integrated, into its devices, a LiDAR sensor capable of providing a 3D model of spaces and objects. The paper presents the studies of their potential about the study and metric documentation of cultural heritage, in particular in cases of extreme urgency and danger of the architectural asset where the speed of survey and non-contact with it becomes relevant.

We focused on the case study of a perimeter wall of a historical building. The survey was performed with two fast and expeditious geomatics methods such as the Close Range Photogrammetry (CRP) and with the LiDAR Apple sensor of the iPad Pro. The wall was also surveyed with Terrestrial Laser Scanner methodology for the validation of the results.

Keywords: Low-cost LiDAR sensor · 3D model · cultural heritage

1 Introduction

The documentation and metric knowledge of the cultural heritage are becoming crucial if we consider the state of degradation of the major part of the historical built heritage and the associated restoration interventions. For these valuable architectures, in-depth metric documentation is fundamental for an overall understanding of these structures, and, in turn, to support architects and engineers in optimizing restoration, conservation, safeguarding and artifact enhancement [1–4]. Recently, however, public funding intended for geometric investigations has been reduced, leading stakeholders and researchers to develop low-cost geomatic tools and methodologies to tackle this necessity, without compromising too much the metric accuracy [5]. In this respect, among the low-cost

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geomatic techniques, multi-image photogrammetry [6–8] is certainly the most effective in facilitating the democratization of the metric documentary process and, thus, in contributing to a wider involvement of users without any specific geomatics expertise.

Via multi-image photogrammetry, it is possible to obtain complete and exhaustive 3D metric surveys with a rapid and intuitive approach [9, 10]. Several examples on this matter are reported in the literature: ranging from architectural applications [11–13] to control and monitoring of structures [14, 15], or environmental and forestry assessments [16–19]. Structure-from-Motion (SfM) algorithm, used in multi-image photogrammetry, produces accurate point clouds with good repeatability [20] and are well suited for the production of metric documentation.

For 3D metric surveys, new miniaturized and low-cost sensors have recently paved the way to cost-effective survey and 3D modeling of buildings or historical-cultural heritage assets. Among the most interesting tools, the laser scanning sensor implemented, since 2020, in Apple devices IPhone (from 12 Pro) and IPad Pro is worth to be mentioned. The complete technical specifications of this sensor - recommended mostly for Augmented Reality (AR) and Virtual Reality (VR) - is not available, but, from the scientific literature, it seems that it consists of a solid-state LiDAR (SSL), i.e. a type of LiDAR which, unlike traditional sensors, does not use motorized mechanical parts (ensuring greater reliability) [21, 22]. The points measured by the LiDAR sensor are combined with the information provided by the RGB camera present in the device and the range declared by Apple is 5 m. Furthermore, from various studies, it seems that there are no differences between the LiDAR sensors mounted on the iPhone and the iPad [23].

The use of the Apple LiDAR sensor is possible only through the dedicated apps that can be downloaded from the App Store. Their combined use allows, in addition to the acquisition of the points, exporting the point cloud and the mesh in various formats. For many apps, it exists: 1) a free-of-charge version, which makes it possible to export merely the mesh and/or point cloud, and 2) a paid version (with a monthly or yearly fee) with more advanced functions targeting mainly metric documentation.

Since the advent of the LiDAR sensor in Apple devices, several apps have been developed and research carried out by research groups to study the geomatic potential and functions of both the sensor and the dedicated apps.

In [24], researchers demonstrate the potential and functionality of both sensors in the IPhone and IPad and of some iOS applications (SiteScape, 3DScanner App, EveryPoint). Accuracies are investigated in different relevant scenarios such as: indoor and outdoor, static or dynamic configuration, and in different types of cultural and architectural heritage (e.g., statues, decorated rooms, and external facades). In addition, concerning heritage documentation, Murtiyos et al. [25] studied the potential of the sensor with respect to multi-image photogrammetry and Terrestrial Laser Scanning on a small object, a facade and a 3D space, using two apps: Every Point and SiteScape. On the other hand, in [26], some geometric aspects of the surveys with the Apple sensor have been addressed: local precision, global correctness and surface coverage for indoor and outdoor environments.

In [27] the accuracy achieved with 4 different apps (among the most used for cultural heritage) are studied on the different assets.

The work presented is a part of a broader research on low-cost geomatics methodologies for the survey of cultural heritage. We focused on the case study of a perimeter wall of a historical building. The survey was performed with two low-cost and fast geomatics methods such as the Close Range Photogrammetry (CRP) by means of a Structure from Motion approach (SfM) and with the LiDAR Apple sensor of the iPad Pro using the app Polycam [28]. The wall was also detected with Terrestrial Laser Scanner methodology for the validation of the results.

2 Materials and Methods

The paper presented is part of a broader research on geomatic methodologies for the survey of cultural heritage with low cost geomatics methodologies. In this context, a perimeter wall of the Institute of Normal Human Anatomy of the University of Cagliari was used as a case study. The building dating back to the early '900 is surrounded by historic walls that, in January 2023, presented cracks that forced the municipality of Cagliari to close the adjacent road. This road is an important access to the historic center of the city. Its closure has created considerable inconvenience to city mobility and therefore the urgent procedure for the restoration of the perimeter wall of the building was immediately activated.

The perimeter wall has a length of about 43 m and for our study 2 distinct parts were chosen called Part 1 (Fig. 1) made of stone without plaster, free of support structures; and Part 2 (Fig. 2), plastered, is the most compromised supported by an iron structure.



Fig. 1. The case study – Part 1



Fig. 2. The case study – Part 2

The property is bound by the Archaeological Superintendence of Fine Arts and Landscape for the metropolitan city of Cagliari and the provinces of Oristano and South Sardinia as a historical-artistic asset and therefore required that all interventions for the safety and restoration of the wall do not modify neither the structure, nor the materials, nor the shape of the wall. The municipality of Cagliari required a fast intervention to speed up the reopening of the road. The works, which started with the urgent procedure, included a geomatic survey of the parts of the wall subject to intervention to document metrically and photographically the parts subject to restoration.

The survey was performed with two fast and expeditious geomatic methods such as the Close Range Photogrammetry (CRP) by means of a Structure from Motion approach (SfM) and with the LiDAR sensor inserted in the iPad Pro, using the Polycam app. The wall was also detected with Terrestrial Laser Scanner methodology for the validation of the two methods. The validation of the point clouds of the LiDAR sensor was performed by means of the CloudCompare software [29].

2.1 Terrestrial Laser Scanner

In order to evaluate the accuracy of the scans performed with the LiDAR sensor, the case study was surveyed with the Faro Focus 3D Terrestrial Laser Scanner.

The Faro Focus 3D Terrestrial Laser Scanner is a compact scanner characterized by an operative range spanning between 0.6 and 120 m, with a ranging error of $\pm$ 2 mm for scanner–object distances between 10 and 25 m.

The scans were processed by using the JRC Reconstructor software v. 3.1.0 by Gexcel Ltd [30]. All clouds from the apps were aligned to those from the TLS by using the JRC Reconstructor software.

For the design of the scans, we started by thinking about the geometry of the wall and the scale of restitution. The presence of architectural details and the situation of

the deformations to be detected were considered. From these considerations, it was decided to perform the scans at a resolution of ¼, with 3x quality, which corresponds to a resolution of 7 mm / 10 m. To ensure an overlap between the scans of at least 30%, 4 scans we made.

Figures 3 and 4 show the point clouds of the two parts of the wall under study. The Point cloud Part 1 had 6.703.748 points, while Point Cloud Part 2 had 9.023.013 points.

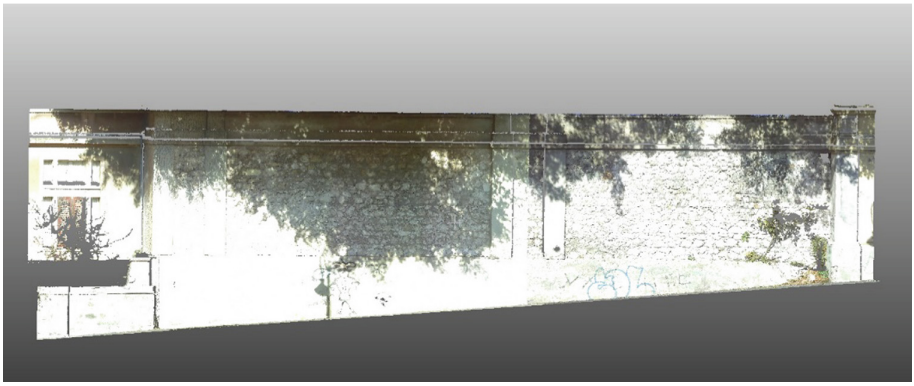


Fig. 3. TLS point cloud – Part 1

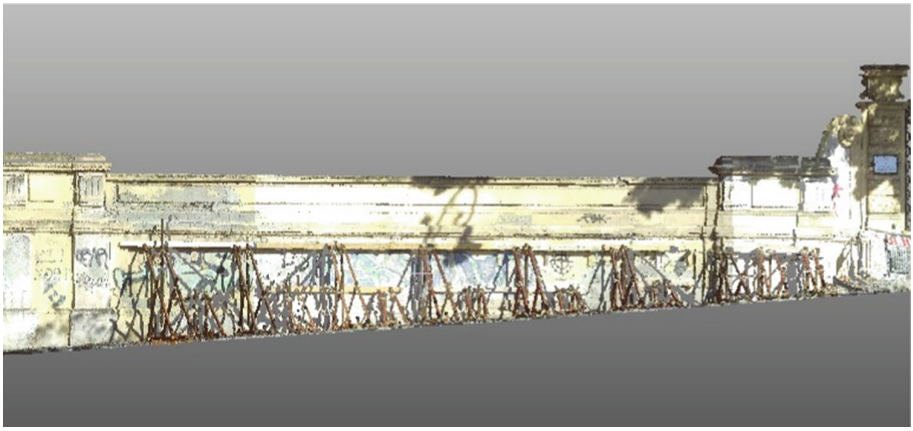


Fig. 4. TLS point cloud – Part 2

2.2 Apple LiDAR sensor Survey

For the geomatics survey with the Apple LiDAR sensor was used the iPad Pro. It has the following specifications: 11" Liquid Retina display, weight of 468 g, 512 GB of memory, 8-core CPU, 8 GB RAM and iOS 15.0.2 software version. It is equipped with a 12MP wide-angle and 10MP ultra-wide-angle RGB camera system and a LiDAR sensor.

Polycam app (version 2.3.9 by charge—Fig. 5) was used for survey. It allows to scan objects by choosing between the LiDAR and ROOM options. This last option allows obtaining, in addition to the point cloud of the scanned room, the horizontal section in dxf format. In the point cloud processing phase, it is possible to choose between Fast (allowing for fast processing for acquisition verification), Space (designed for space scans), Object (for object scans) and Custom modes. For the Custom mode, it is possible to choose the Depth Range (from 0.1 to 6 m), the Voxel Size (from 3 mm to 27 mm) and the simplification to be applied to the mesh (in percentage). Polycam was purchased, at a cost of $6.99/month, allowing us to export the point clouds in different formats (a possibility prevented in the free version, which is capable of ex-porting only the mesh in glTF format). The two parts of the wall were taken over separately. The survey was carried out by holding iPad always parallel to the wall object of the survey and at distance about 2 m. The scan was processed in the "Space" mode.

In Fig. 6 it can be seen how, especially for Part 1, the scan was not able to include the entire height of the wall. This is due to the Apple LiDAR sensor's range of only 5m. To get the whole scan of Part 1 we will have to use a ladder or other support to pick up the Ipad Pro from the ground. Figure 7 shows the complete Part 2 scan.

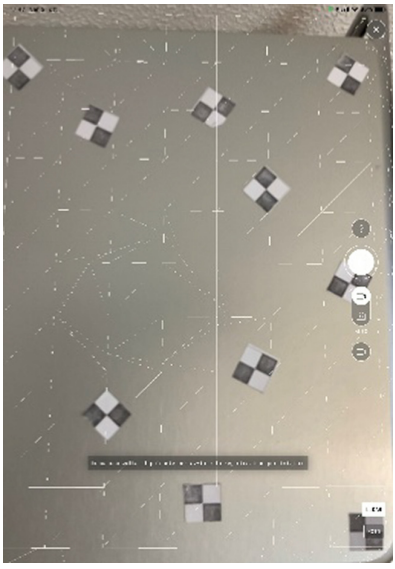


Fig. 5. Polycam App



Fig. 6. Apple LiDAR sensor point cloud – Part 1

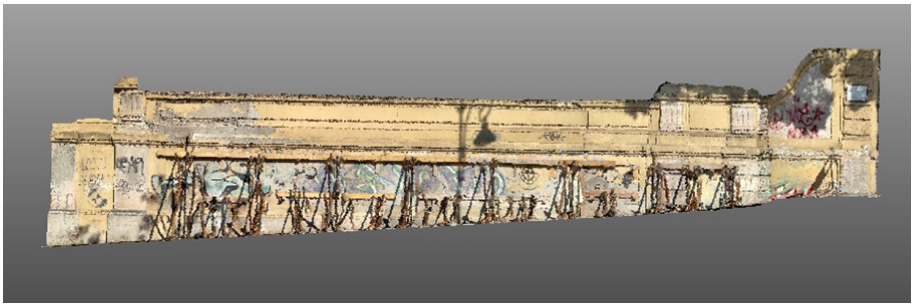


Fig. 7. Apple LiDAR sensor point cloud – Part 2

The Point cloud Part 1 had 651.409 points, while Point Cloud Part 2 had 2.830.747points.

2.3 Close Range Photogrammetry Survey

The wall was also surveyed with the Close Range Photogrammetry technique.

The low-cost Close Range Photogrammetric (CRP) system included non-professional digital camera Canon EOS M3 with a sensor CMOS 22.3x14.9 mm and a 24.2 Megapixel resolution; objective EF-S 18–55 mm; the output data formats are Exif 2.3 (JPEG) and RAW (CR2 Canon original). The images were processed with the Metashape commercial software by Agisoft That implements the Structure from Motion (SfM) algorithm. The SfM is a low-cost photogrammetric method for high-resolution topographic reconstructions. The SfM operates under the same basic tenets of the stereoscopic photogrammetry. However, they fundamentally differ because in SfM the geometry of the scene, camera positions and orientation are solved automatically without points known. In the other method, instead, points are solved simultaneously using a

highly redundant, iterative bundle adjustment procedure, based on a database of features automatically extracted from a set of multiple images with a high degree of overlap [31].

The Metashape workflows consist in the following main steps: image import, image alignment, generation of the sparse point cloud, optimization of image alignment, georeferenced, generation of the dense point cloud, generation DEM and generation orthophoto.

Photogrammetric surveys were carried out for both parts of the wall by taking images with the optical axis as orthogonal to the wall as possible. A total of 66 images were taken for the Part 1 and 55 images for the Part 2.

The image processing workflow follows the standard steps of SfM software with the solution of the Bundle Adjustment on sparse point cloud, external orientation of the block and generation of the dense point cloud. All images have been elaborated in Medium mode, in fact, as verified in [1] the accuracy does not vary with respect to UltraHigh mode and processing times are reduced.

The Point Cloud 1 had 2,470,590 points (Fig. 8), while Point Cloud 2 had 4,325,094 points (Fig. 9).

The CRP point cloud was georeferenced using 6 GCPs extracted from the TLS point cloud. The global RMS of georeferencing was about 2 cm.

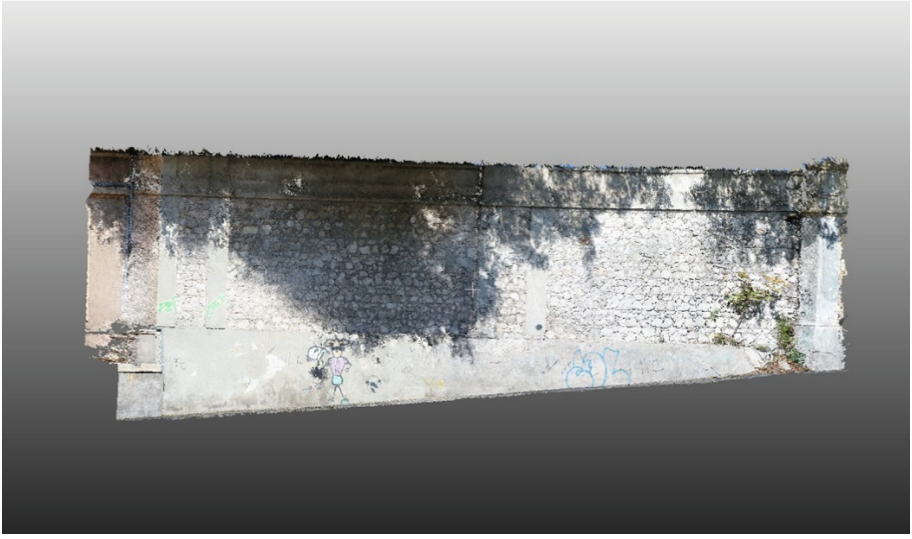


Fig. 8. CRP point cloud – Part 1



Fig. 9. CRP point cloud – Part 2

3 Results

Point clouds from the Appel LiDAR sensor and CRP were compared with each other and validated with the point cloud from TLS.

The validation of the point clouds was performed by means of the CloudCompare software [29] and, specifically, using Cloud-to-Cloud Distance (C2C) tool. Cloud-to-cloud (C2C) analysis calculates the minimal distance between every point of the models using the nearest neighbour algorithm. Furthermore, the software allows the evaluation of statistical parameters, such as the minimal distance, maximal distance, average distance, and standard deviation.

Below are the results of the comparisons made between point clouds.

3.1 Apple LiDAR Sensor vs CRP

The first comparison is between the survey Apple LiDAR point cloud and the CRP point cloud. Table 1 shows the statistical parameters associated to these comparisons.

Figures 10 and 11 show the results of this comparison.

Table 1. C2C analysis - Statistical parameters of the comparisons between the Apple LiDAR sensor and the CRP point clouds.

	Part 1	Part 2
Min (m)	0	0
Max (m)	0.199	0.709
Mean (m)	0.005	0.056
Dev. Stand (m)	0.030	0.128

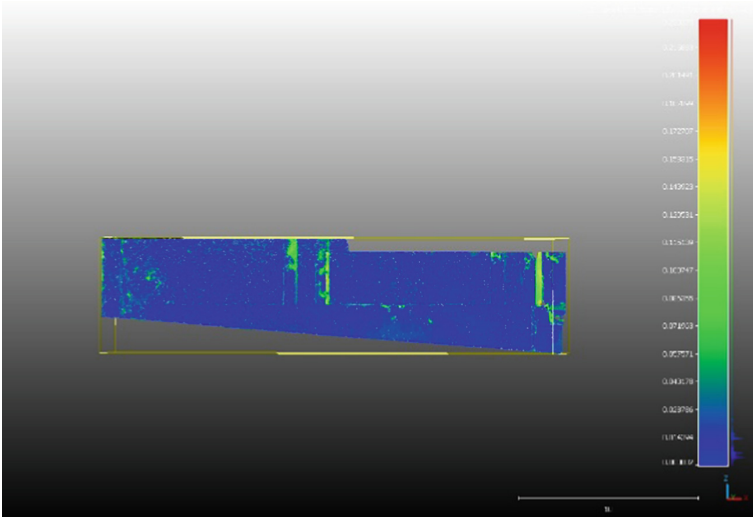


Fig. 10. Discrepancy (m) map between Apple LiDAR and the CRP point clouds – Part 1.

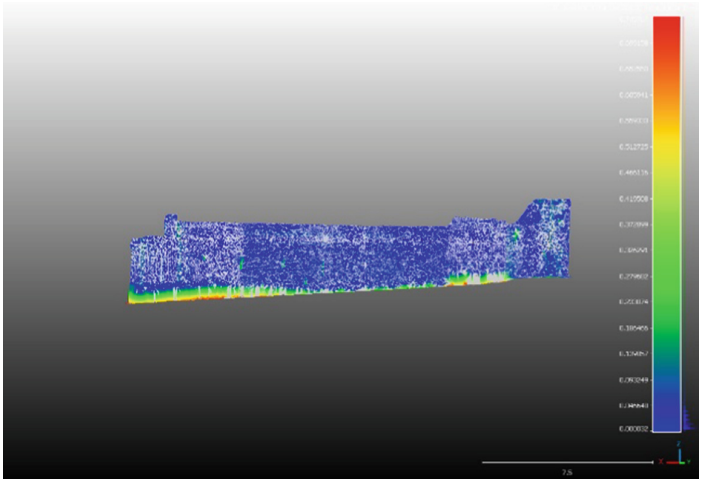


Fig. 11. Discrepancy (m) map between Apple LiDAR and the CRP point clouds – Part 2.

3.2 Apple LiDAR Sensor vs TLS

The second comparison performed is between the survey with the Apple LiDAR sensor and the Terrestrial Laser Scanner. To evaluate the accuracy of the point clouds, they were compared via the Cloud-to-cloud (C2C) analysis. Table 2 shows the statistical parameters associated to these comparisons. Figures 12 and 13 show the results of this comparison.

Table 2. C2C analysis - Statistical parameters of the comparisons between the Apple LiDAR sensor and the TLS point clouds.

	Part 1	Part 2
Min (m)	0	0
Max (m)	0.629	0.287
Mean (m)	0.005	0.011
Dev. Stand (m)	0.038	0.037

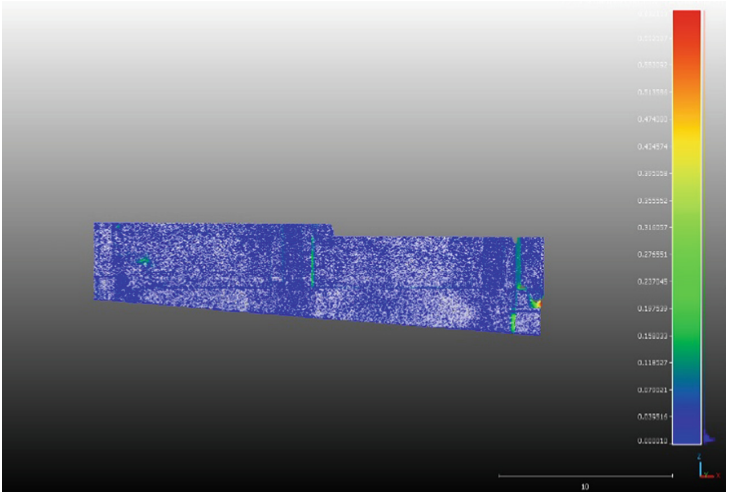


Fig. 12. Discrepancy (m) map between Apple LiDAR and the TLS point clouds – Part 1

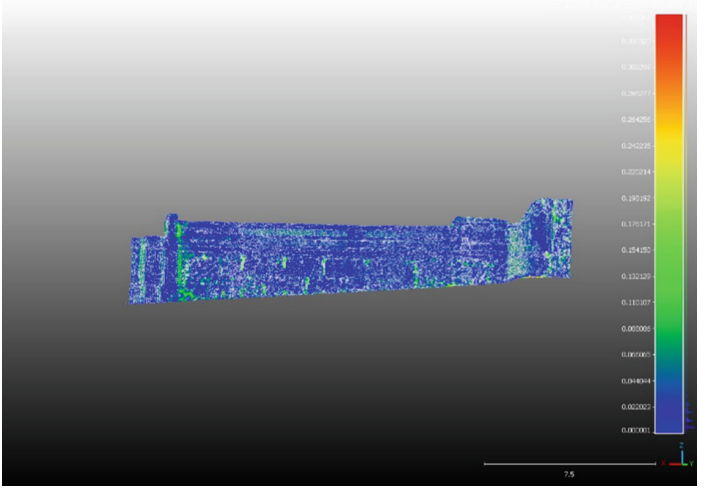


Fig. 13. Discrepancy (m) map between Apple LiDAR and the TLS point clouds – Part 2

3.3 TLS Vs CRP

The third comparison performed is between the survey with the Terrestrial Laser Scanner and the Close Range Photogrammetry. To evaluate the accuracy of the point clouds, they were compared via the Cloud-to-cloud (C2C) analysis.

Table 3 shows the statistical parameters associated to these comparisons.

Figures 14 and 15 show the results of this comparison.

Table 3. C2C analysis - Statistical parameters of the comparisons between the TLS and the CRP point clouds.

	Part 1	Part 2
Min (m)	0	0
Max (m)	0.660	0.316
Mean (m)	0.006	0.006
Dev. Stand (m)	0.039	0.027

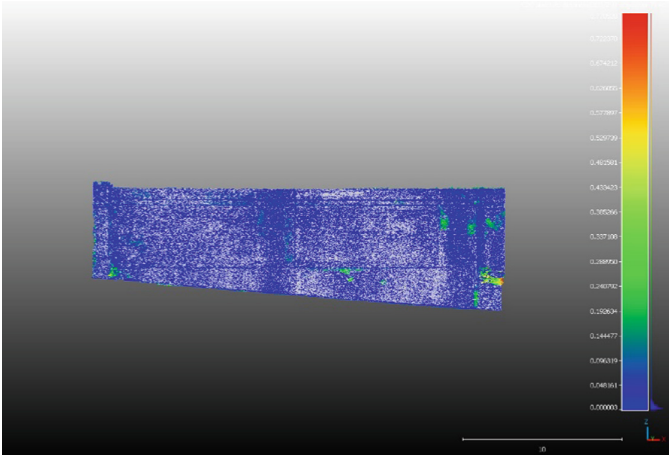


Fig. 14. Discrepancy (m) map between TLS and the CRP point clouds – Part 1.

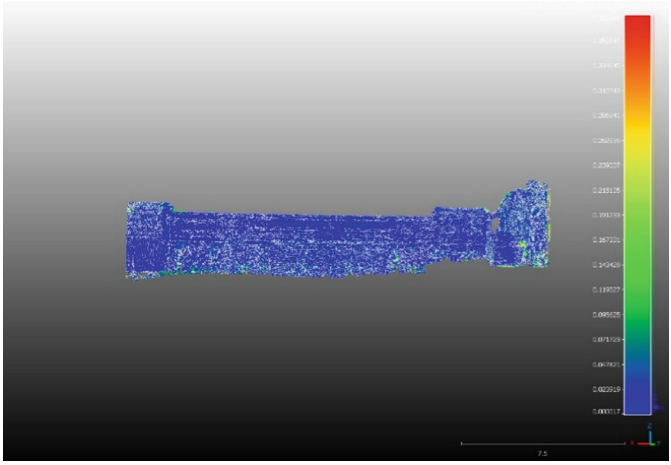


Fig. 15. Discrepancy (m) map between TLS and the CRP point clouds – Part 2.

4 Discussion and Conclusion

We investigated the accuracy of the low cost geomatics methodologies and techniques, in particular we studied the potential of Apple Lidar sensor incorporated into the latest generation of Apple iPad and the Close Range Photogrammetry with low cost digital camera for the 3D models acquisition of historical, cultural, and architectural heritage assets.

From these results we dare to assert that, in line with other research, both CRP and Apple LiDAR geomatics methodologies can be a valuable tool for the 3D models creating of architectural and cultural heritage [32], providing the possibility to contribute to the metric documentation required in the process of knowledge of the asset. However, it is necessary to pay particular attention to survey mode, especially for the Apple LiDAR sensor. This attention is due to the range of the Apple LiDAR sensor of only 5 m. This limitation, in fact, provides for the use of survey supports in order to access the upper parts of the architectural asset such as stairs or elevators and to provide more scans that must subsequently be joined. This attention will allow you to survey assets wider than the range provided by Apple.

From these researches it therefore seems that these new devices and associated opportunities pave the way for faster production of metric documentation which can be crucial, for example, in emergencies and with limited funds available.

References

1. Barsanti, S.G., Remondino, F., Fenández-Palacios, B.J., Visintini, D.: Critical factors and guidelines for 3D surveying and modelling in cultural heritage. Int. J. Heritage Digital Era **3**(1), 141–158 (2014)
2. Munumer, E., Lerma, J.L.: Fusion of 3D data from different image-based and range-based sources for efficient heritage recording. Digital Heritage **2015**, 83–86 (2015)

3. Deidda, M., Musa, C., Vacca, G.: A GIS of Sardinia's coastal defense system (XVI – XVIII Century). Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XL-4/W7**, 17–22 (2015). https://doi.org/10.5194/isprsarchives-XL-4-W7-17-2015
4. Giannattasio, C., Grillo, S.M., Vacca, G.: Interdisciplinary study for knowledge and dating of the San Francesco convent in Stampace, Cagliari – Italy (XIII-XXI Century). ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. **II-5/W1**, 139–144 (2013). https://doi.org/10.5194/isprsannals-II-5-W1-139-2013
5. Nocerino, E., et al.: A smartphone-based 3D pipeline for the creative industry – the replicate EU project. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLII-2/W3**, 535–541 (2017). https://doi.org/10.5194/isprs-archives-XLII-2-W3-535-2017
6. Vacca, G.: UAV photogrammetry for volume calculations. a case study of an open sand quarry. In: Gervasi, O., Murgante, B., Misra, S., Ana, M.A., Rocha, C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops: Malaga, Spain, July 4–7, 2022, Proceedings, Part VI, pp. 505–518. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-10592-0_36
7. Brandolini, F., Patrucco, G.: Structure-From-Motion (SFM) photogrammetry as a non-invasive methodology to digitalize historical documents: a highly flexible and low-cost approach? Heritage **2**, 2124–2136 (2019). https://doi.org/10.3390/heritage2030128
8. Parrinello, S., Dell'Amico, A.: Experience of documentation for the accessibility of widespread cultural heritage. Heritage **2**, 1032–1044 (2019). https://doi.org/10.3390/heritage2010067
9. Janiszewski, M., Torkan, M., Uotinen, L., Rinne, M.: Rapid photogrammetry with a 360-degree camera for tunnel mapping. Remote Sens. **14**, 5494 (2022). https://doi.org/10.3390/rs14215494
10. Teppati Losè, L., Chiabrando, F., Giulio Tonolo, F.: Documentation of complex environments using 360° cameras. The Santa Marta Belltower in Montanaro. Remote Sens. **13**, 3633 (2021)
11. Vacca, G., Dessi A.: Geomatics supporting knowledge of cultural heritage aimed at recovery and restoration. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. 43, 909–915 (2022)
12. Grillo, S.M., Pilia, E., Vacca, G.: Integrated study of the Beata Vergine Assunta dome with Structure from Motion and diagnostic approaches. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLII-2/W11**, 579–585 (2019). https://doi.org/10.5194/isprs-archives-XLII-2-W11-579-2019
13. Aita, D., Barsotti, R., Bennati, S., Caroti, G., Piemonte, A.: 3-dimensional geometric survey and structural modelling of the dome of Pisa cathedral. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-2/W3, 39–46 (2017). https://doi.org/10.5194/isprs-archives-XLII-2-W3-39-2017
14. Park, G., Lee, J.H., Yoon, H.: Semantic structure from motion for railroad bridges using deep learning. Appl. Sci. **11**, 4332 (2021). https://doi.org/10.3390/app11104332
15. Mandirola, M., Casarotti, C., Peloso, S., Lanese, I., Brunesi, E., Senaldi, I.: Use of UAS for damage inspection and assessment of bridge infrastructures, Int. J. Disaster Risk Reduction, **72**, 102824, ISSN 2212-4209 (2022). https://doi.org/10.1016/j.ijdrr.2022.102824
16. Garcia Millan, V.E., Rankine, C., Sanchez-Azofeifa, G.A.: Crop loss evaluation using digital surface models from unmanned aerial vehicles data. Remote Sens. **12**, 981 (2020). https://doi.org/10.3390/rs12060981
17. Hasheminasab, S.M., Zhou, T., Habib, A.: GNSS/INS-assisted structure from motion strategies for UAV-based imagery over mechanized agricultural fields. Remote Sens. **12**, 351 (2020). https://doi.org/10.3390/rs12030351
18. Grottoli, E., Biausque, M., Rogers, D., Jackson, D.W.T., Cooper, J.A.G.: Structure-from-motion-derived digital surface models from historical aerial photographs: a new 3D application for coastal dune monitoring. Remote Sens.13, 95 (2021). https://doi.org/10.3390/rs13010095

19. Vacca, G.: Estimating tree height using low-cost UAV. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. **XLVIII-M-1–2023**, 381–386 (2023). https://doi.org/10.5194/isprs-archives-XLVIII-M-1-2023-381-2023
20. De Marco, J., Maset, E., Cucchiaro, S., Beinat, A., Cazorzi, F.: Assessing repeatability and reproducibility of structure from-motion photogrammetry for 3D terrain mapping of riverbeds. Remote Sens. **13**, 2572 (2021). https://doi.org/10.3390/rs13132572
21. García-Gómez, P., Royo, S., Rodrigo, N., Casas, J.R.: Geometric model and calibration method for a solid-state LiDAR. Sensors **20**, 2898 (2020)
22. Wang, D., Watkins, C., Xie, H.: MEMS mirrors for LiDAR: a review. Micromachines **11**, 456 (2020)
23. Luetzenburg, G., Kroon, A., Bjørk, A.A.: Evaluation of the Apple iPhone 12 Pro LiDAR for an application in geosciences. Sci. Rep. **11**, 22221 (2021)
24. Teppati Losè, L., Spreafico, A., Chiabrando, F., Giulio Tonolo, F.: Apple LiDAR sensor for 3D surveying: tests and results in the cultural heritage domain. Remote Sens. **14**, 4157 (2022). https://doi.org/10.3390/rs14174157
25. Murtiyoso, A., Grussenmeyer, P., Landes, T., Macher, H.: First assessments into the use of commercial-grade solid state lidar for low cost heritage documentation. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIII-B2–2, 599–604 (2021)
26. Díaz-Vilariño, L., Tran, H., Frías, E., Balado, J., Khoshelham, K.: 3D mapping of indoor and outdoor environments using Apple smart devices, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLIII-B4–2022, 303–308 (2022). https://doi.org/10.5194/isprs-archives-XLIII-B4-2022-303-2022
27. Vacca, G.: 3D Survey with Apple LiDAR Sensor—test and assessment for architectural and cultural heritage. Heritage **6**, 1476–1501 (2023). https://doi.org/10.3390/heritage6020080
28. PolyCam https://poly.cam/. Accessed 5 Oct 2022
29. https://www.cloudcompare.org/main.html
30. https://gexcel.it/it/software/reconstructor
31. Szeliski, R.: Computer vision: algorithms and applications. Springer, London (2010). https://doi.org/10.1007/978-1-84882-935-0
32. Vacca, G., Quaquero, E.: BIM-3D GIS: an integrated system for the knowledge process of the buildings. J. Spatial Sci. **65**(2), 193–208 (2019). https://doi.org/10.1080/14498596.2019