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Reviewer A: Round 1
Date completed: 05 May 2023
Recommendation: Accept / Revisions required / **Resubmit for review** / Decline
Conflicts of interest: None

Does the manuscript fall within the scope of SAJS?
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Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No
Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No
Do the Title and Abstract clearly and accurately reflect the content of the manuscript?
Yes/No
Is the research problem significant and concisely stated?
Yes/**No**
Are the methods described comprehensively?
Yes/No
Is the statistical treatment appropriate?
Yes/No/**Not applicable**/Not qualified to judge
Are the interpretations and conclusions justified by the research results?
Yes/Partly/No
Please rate the manuscript on overall contribution to the field
Excellent/**Good**/Average/Below average/Poor
Please rate the manuscript on language, grammar and tone
Excellent/**Good**/Average/Below average/Poor
Is the manuscript succinct and free of repetition and redundancies?
Yes/**No**
Are the results and discussion confined to relevance to the objective(s)?
Yes/No
The number of tables in the manuscript is
Too few/**Adequate**/Too many/Not applicable
The number of figures in the manuscript is
Too few/Adequate/**Too many**/Not applicable
Is the supplementary material relevant and separated appropriately from the main document?
Yes/**No**/Not applicable
Please rate the manuscript on overall quality
Excellent/Good/**Average**/Below average/Poor

Is appropriate and adequate reference made to other work in the field?

Yes/**No**

Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates?

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Comments to the Author:

Thank you for submitting this article for review. The findings are very relevant to the broader scientific community. Still, due to the practical nature of the findings, it might become dated quickly, i.e. with the launch of improved iPhone LiDAR or the sales of lower-cost LiDAR devices. Regardless, reviewing this paper as indicated in my comments (attached) or submitting it to a related conference will be a worthwhile contribution to the field. It might be of value to generalise the findings to theories that might explain or predict the growth or development of low-cost devices.

The paper can be improved by including the appropriate references/citations to support the claims made, mainly in the introduction section, and by including related research on previous or related studies on the accuracy of iPhone LiDAR in the literature review. Writing and citation styles can also be improved (made more concise/precise).

[See attachment for further comments by this reviewer]

[See Appendix 1 for Reviewer A's comments made directly on the manuscript]

Author response to Reviewer A: Round 1

Is the research problem significant and concisely stated? No

AUTHOR: Thank you for highlighting this point. To address this we have reworked the introduction and in its last paragraph we concisely state the research problem and thereafter the research aims.

Is the manuscript succinct and free of repetition and redundancies? No

AUTHOR:Noted ,you will notice we have cleaned the document and combed out repetitive and redundant information. An example is in the tables , initially we had three tables that were highlighting related information but we have summarised this in words instead and retained only one table

Is appropriate and adequate reference made to other work in the field? No

AUTHOR:There has been a complete re-do of reference in text and on the list. Kindly check and you will note that our referencing is updated and missing references were also added

Thank you for submitting this article for review. The findings are very relevant to the broader scientific community. Still, due to the practical nature of the findings, it might become dated quickly, i.e. with the launch of improved iPhone LiDAR or the sales of lower-cost LiDAR devices. Regardless, reviewing this paper as indicated in my comments (attached) or submitting it to a related conference will be a worthwhile contribution to the field. It might be of value to generalise the findings to theories that might explain or predict the growth or development of low-cost devices.

The paper can be improved by including the appropriate references/citations to support the claims made, mainly in the introduction section, and by including related research on previous or related studies on the accuracy of iPhone LiDAR in the literature review. Writing and citation styles can also be improved (made more concise/precise).

[See attachment for further comments by this reviewer]

AUTHOR:We are encouraged that our work is of relevance of the broader scientific audience. We note the important point that the nature of this work it is key to highlight to the reader some theory on adoption of technologies. This will ensure they can easily tweak our findings to the latest technology that they will hold in their hands later should they encounter our work somewhere.

This has been added to the start of the theory and literature section. See the very first paragraph and the first few lines that highlight this point.

The literature and referencing related comments have been addressed as highlighted in the point above.

Thank you very much. This is encouraging. We appreciate your reading our work and giving input to improve the work!

Reviewer B: Round 1
Date completed: 12 September 2023
Recommendation: Accept / Revisions required / **Resubmit for review** / Decline
Conflicts of interest: None

Recommendation and comments submitted offline. Full online report not completed.

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Yes/No

Comments to the Author:

After reading through the paper I saw a few issues that need serious attention and these are:

1. The author(s) must ensure that all the information from other sources is referenced. Line 36 – 182 there are no reference and most of the information is coming from other sources.
2. The author(s) must ensure all abbreviations are written in full on first mention
3. There is a mix between results (outcomes) and methodology (what was done). The author(s) must move what was done in the methodology section and outcomes in the results section. Also in the methodology section the author(s) must ensure that its easy to follow what was done (for repeatability purposes). In the results section the font size for tables must be uniform and must be captioned uniformly. There words like above or below must be avoided the author(s) must cross-reference to the exact figure or table. Some of the figures and table are not cross referenced.
4. In the results the author(s) must benchmark the findings against existing literature.
5. The author(s) must use a uniform reference system. There are some superscripted numbers in the documents without corresponding footnotes.

Overall the research is quite novel and if these issues are properly addressed it will allow us to properly review the science.

Author response to Reviewer B: Round 1

The author(s) must ensure that all the information from other sources is referenced. Line 36 –182 there are no reference and most of the information is coming from other sources.

AUTHOR: Noted with thanks and updated accordingly.

The author(s) must ensure all abbreviations are written in full on first mention
AUTHOR: Done throughout document on the first use of an acronym.
There is a mix between results (outcomes) and methodology (what was done). The author(s) must move what was done in the methodology section and outcomes in the results section. Also in the methodology section the author(s) must ensure that its easy to follow what was done (for repeatability purposes). In the results section the font size for tables must be uniform and must be captioned uniformly. There words like above or below must be avoided the author(s) must cross-reference to the exact figure or table. Some of the figures and table are not cross referenced.
AUTHOR: Separated accordingly, see manuscript. A large portion of the results has been moved out into discussion in cases where it was discussing the reasons for a result and not so much the result itself.
In the results the author(s) must benchmark the findings against existing literature.
AUTHOR: There has not been much done to our level of detail but have included in commentary form in line with a few sources cited in literature section of paper. See discussions.
The author(s) must use a uniform reference system. There are some superscripted numbers in the documents without corresponding footnotes.
AUTHOR: Done, APA used as per journal guidelines
Overall the research is quite novel and if these issues are properly addressed it will allow us to properly review the science.
AUTHOR: Thank you very much. This is encouraging. We appreciate your reading our work and giving input to improve the work!

Reviewer B: Round 2
Date completed: 29 February 2024
Recommendation: Accept / **Revisions required** / Resubmit for review / Decline
Conflicts of interest: None

Does the manuscript fall within the scope of SAJS?
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Is the manuscript written in a style suitable for a non-specialist and is it of wider interest than to specialists alone?
Yes/No
Does the manuscript contain sufficient novel and significant information to justify publication?
Yes/No
Do the Title and Abstract clearly and accurately reflect the content of the manuscript?
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Is the research problem significant and concisely stated?
Yes/No
Are the methods described comprehensively?
Yes/No
Is the statistical treatment appropriate?
Yes/No/**Not applicable**/Not qualified to judge
Are the interpretations and conclusions justified by the research results?
Yes/Partly/No
Please rate the manuscript on overall contribution to the field
Excellent/**Good**/Average/Below average/Poor
Please rate the manuscript on language, grammar and tone
Excellent/**Good**/Average/Below average/Poor
Is the manuscript succinct and free of repetition and redundancies?
Yes/No
Are the results and discussion confined to relevance to the objective(s)?

Yes/No
The number of tables in the manuscript is
Too few/**Adequate**/Too many/Not applicable
The number of figures in the manuscript is
Too few/**Adequate**/Too many/Not applicable
Is the supplementary material relevant and separated appropriately from the main document?
Yes/No/**Not applicable**
Please rate the manuscript on overall quality
Excellent/**Good**/Average/Below average/Poor
Is appropriate and adequate reference made to other work in the field?
Yes/**No**
Is it stated that ethical approval was granted by an institutional ethics committee for studies involving human subjects and non-human vertebrates?
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Yes/No
Comments to the Author: Hi Author, 1. Can you please ensure that all the INFORMATION FROM OTHER SOURCES IS ACKNOWLEDGED 2. In the RESULT SECTION CAN YOU MOVE What you did (methodology) to the method section and remain with your outcome (Results) 3. Check comments on the attached document and address them accordingly

[See Appendix 2 for Reviewer B's comments made directly on the manuscript]

Author response to Reviewer B: Round 2

[See Appendix 3 for Author's comments made directly on the manuscript]

Appendix 1: Reviewer A comments on manuscript

MOBILE PHONE BASED LiDAR AS A LOW-COST ALTERNATIVE FOR TRANSDISCPLINARY DATA COLLECTION

Abstract

Airborne and terrestrial laser scanning have traditionally been used as a specialised toolset for scene capture in engineering using expensive commercial grade of these instruments w remains expensive and sensitive during handling. The recent inclusion of a LiDAR sensor by mobile phone manufacturers such as Apple is now analogous to the integration of the global navigation satellite systems (GNSS) and cameras into phones decades ago. It is likely that initial efforts to include the LiDAR sensor in mobile phones will see rapid improvements in the uses and accuracy of the sensor. There is a growing and broad application of LiDAR for transdisciplinary and recreational purposes that has been made even more accessible to iPhone users. The problem lies in the limited amount of literature that benchmarks emerging and low-cost LiDAR sensors to existing commercial ones. There is therefore a need for researchers to evaluate and provide evidence that can assist users who may need to use the technology for various applications. This study investigated the extent to which an iPhone LiDAR tools available within the iPhone 12 Pro compare to the engineering grade laser scanner. The methodology described in the paper includes point positioning using the iPhone and reference laser scanner point clouds. Outcomes from the research showed that iPhone GNSS receivers can deliver the required models albeit being relatively unstable when pitched against traditional LiDAR scanners and they introduce some positional shift and scan drift as a primary error source.

Keywords: SDG11 (Sustainable cities and communities LiDAR, Transdisciplinary, Scanning, accuracy, low cost, iLiDAR

Significance of the main findings

The aim of this study is to evaluate the accuracy that the iPhone 12 Pro (iLiDAR) scanner with respect to commercial grade point clouds. The results show that iLiDAR performed well as a fit for purpose application or tool. However, it was noted that for highly accurate work, its GNSS capability failed to provide adequate absolute accuracy as anticipated. To address the possible methods of providing optimal results from the iLiDAR system, it is with strong recommendation that a proper stabilizer be used for the acquisition of the iLiDAR if greatest accuracy is desired. The significance of this work is in presenting an opportunity for transdisciplinary projects to incorporate LiDAR data usage, in instances where digital models of various subjects are required for further analysis or measurement. The paper is appealing to a broad scientific and non-scientific audience.

1.0 Introduction, Background and Aims

Lidar systems have over the years allowed users to create observations of any man made or environmental structure for application in hundreds of areas such as geology, archaeology, engineering, and spatial data collection. Airborne and terrestrial laser scanning have traditionally been used by engineers as a specialised toolset for scene capture, providing highly accurate measurements with minimal human interaction. However, the commercial grade of these instruments remains expensive and sensitive during handling thus requiring routine calibrations to ensure their functionality and value remains a priority. The recent inclusion of a LiDAR sensor by mobile phone manufacturers such as Apple is now analogous to the integration of the global navigation satellite systems (GNSS) and cameras into phones decades ago.

Scanning methods provide of quick and accurate data capture at increased rates and the approach services multiple users across the technical context of aerial (ALS), mobile (MLS) and terrestrial laser scanning (TLS) applications. Furthermore, terrestrial laser scanning using high grade equipment provides large volumes of point cloud data with high resolution for topographic mapping, meteorology, archaeology, monitoring deformation, building construction and structure analysis in engineering surveys[1]. These numerous applications have led rapid developments in mechanical and data processing capabilities attempting make the systems more accurate, efficient, and affordable to a larger market. Since 2007, when the first iPhone was announced, there has been an increase in similar high-end mobile phone interfaces that have claimed to revolutionize many professional disciplines, by offering mass integration of distinguishable technologies with varied purposes, into mobile devices [2]. The bloom in popularity of Apple's iPhone is driven by its constant innovations and out of the box utilities. Of recent, Apple's ambition to improve themselves has led to the inclusion of their 1st Gen LiDAR (hereinafter referred to as iLIDAR) sensor incorporated into their new iPad Pro and iPhone 12 Pro models and devices beyond. These sensors function on the same scientific concepts as their professional grade counterparts albeit reduced to the most basic components. The incorporation of this LiDAR sensor into the phone was intended at improving their Measure Application (app) capabilities by introducing depth sensing, portrait image capability, night mode performance, and Augmented and Virtual video game functionality. After the introduction of the LiDAR sensor in the mobile gadget, third party applications (apps) capitalized on the opportunity to use this LiDAR system in conjunction with the processing power of its new bionic core, to provide 3D models just as terrestrial LiDAR systems would. The three-dimensional (3D) models appealed to multiple disciplines who could use the iLiDAR for reality capture and documentation. Therefore, the additional ability to reconstruct 3D models using the iLiDAR is not accredited to Apple, but several third-party sources who developed these apps to take advantage of the LiDAR system using the app developer's designed algorithm. These apps can produce well textured models through use of a simultaneous localisation and mapping (SLAM) algorithm, Simultaneous Localization and Mapping, which in practice allows for the construction of maps and models through the continuous updating of results using precise determinations of the scanner's location and orientation. This algorithm is used primarily for mobile laser scanning (MLS), as the LiDAR scanner is mounted to some vehicle with the Global Navigation Satellite System (GNSS) and Inertial Measurement nit (IMU) systems constantly keeping track of the vehicle during acquisition, where the SLAM algorithm allows for a registration and geo-referencing of all these points. In the research done by [3] (Luetzenburg, G., et al 2021) they concluded that the accuracy of the iLiDAR systems fluctuates between 3cm and 6cm, which demonstrates a high potential for the mapping of small-scale scenes such as residential rooms above. Apart from its use in gaming these capabilities are promising for forensics, real estate, physics, archaeology, and engineering documentation. Despite the rapid growth to increase reach, the addition of these added specialised competences to selected mobile phone would require immense focus on obtaining accurate measurements in real time, and with consideration that professional scanners require maintenance to provide quality data. It is therefore interesting to benchmark these lower cost sensors to engineering grade. Engineering grade laser scanners are specialized equipment to attain spatial data effectively and accurately, however, at a prohibitive cost of R600, 000 to R2, 000,000, in addition to routine maintenance to ensure its delivered accuracy. The iPhone 12 Pro and better, costing above R20, 000, now provides LiDAR capabilities to the public which claim to provide comparable results, requiring no maintenance and real time processing. Literature posits that there is insufficient scientific knowledge on the iLiDAR capabilities as there are very few studies that have captured the gains of this recent development from an accuracy perspective. This creates a gap in knowledge in terms of the applicability of this low-cost technology to multiple uses. This paper focuses on testing the accuracy of the iPhone's LiDAR sensor and its capabilities with respect to terrestrial laser scanner derived point clouds. Monitoring how different technologies are being incorporated into existing technologies and how fast they grow in complexity will give an insight into the accuracy available for future data collection options. The study also articulates on the accuracy that the iPhone 12 Pro LiDAR scanner in relation to its GNSS positional accuracy while scanning for point clouds.

2.0: Associated theories and literature review

The measurement principles behind LiDAR scanning are to juxtapose the numerous benefits and applications of the technology, sharing similar base concept of electronic distance measurements. LiDAR is at its core is a range detection method using a laser pulse to illuminate an object and measuring the time taken for this pulse to return to the source allowing the LiDAR scanner to accurately measure the distance between the sensor and the object. From the interaction of the laser pulse with an environment a three-dimensional impression of the real world is recreated with a collection of X, Y and Z coordinates for multiple locations. LiDAR sensing under low light condition providing overall accuracies of 0.191 metres (m), 0.242m, 0.345m at 20m, 40m, 60m altitudes [4]. Commercial terrestrial and mobile scanner such as those depicted in Figure 1 b) and c) below can achieve an accuracy of less than 20 millimetres (mm) for TOF scanner and less than 10mm for phase difference scanner [5]. It should be noted that this is a very general estimate due to the wide range of LiDAR scanners available on the market, as many can provide between 3mm and 6mm accuracies. Mobile laser scanning takes the concept of terrestrial or ground based laser scanning but by adding a real time kinematic GNSS and inertial measurement unit (IMU) systems for a moving platform. This allows scanning to take place in rapid succession by driving a LiDAR scanner mounted to a vehicle/platform and producing a geo-referenced point cloud through registration. Figure 1 below depicts the different scan mechanisms and a typical airborne scan product.

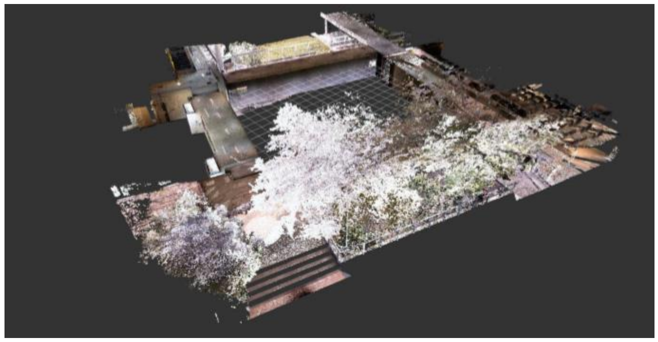

Figure 1: A typical ALS scanner deliverable from a built up site [Source: own compilation]

The iPhone LiDAR scanner on the other hand is a combination of all the iPhone 12 Pro sensors that provides it, and its later variants, with the potential to approximate engineering grade mapping capabilities as it combines a refined GNSS receiver, enhanced gyroscope, and accelerometer sensor as well as what is described as a high precision camera sensors and LiDAR sensor. In the research done by [6] (Tavani et al ,2022) the author described the iPhone 12 Pro LiDAR system as a paradigm shift, improving the geospatial data acquisition process through acquiring three-dimensional (3D) reconstruction models for fieldwork in real time. The study concluded that such a capability in the hands of scientist, such as geologists, would improve research fieldwork opportunities by increasing access to low-cost LiDAR data, and enhancing repeatability and transparency [6]. Figure 2 below depicts the iLiDAR sensor location and projection area. iLiDAR scans which use a defined grid of points in the sensor to measure the object and using the SLAM algorithm which calibrates the LiDAR sensor to work directly with the camera sensors to allow real time visualization of an object. This algorithm uses the gyroscope and accelerometer to measure the iPhones orientation in space, acting as an inertial measurement unit (IMU) system allowing the iPhone to move and scan more points around the object [7]. This results in a complete point cloud which utilizes the high-end camera system to construct an RGB scalar field for the point cloud and is primarily applicable for meter scale scenes. Among these iLiDAR apps include 3D Scanner App, Pix4DCatch, Polycam, Every Point (which integrates LiDAR with photogrammetry) and SiteScape.

Figure 2 iPhone 12 Pro LiDAR sensor [Source: Wikimedia Creative Commons License for open use]

It is possible to add location or GNSS capability using the iPhone 12 Pro GNSS receiver, however, due to the low resolution available to these sensors, absolute accuracy will not approach engineering grade standards. ~~However, in a study conducted by~~ [7] ~~(~~ Tamimi, R. 2022) , ~~they~~ concluded that the use of an external RTK GNSS receiver connected to the iPhone 12 via Bluetooth, may provide much higher accuracies by using much more defined positional information. It is, therefore, the purposes of this research to evaluate whether the same is true without the RTK receiver, not to evaluate absolute accuracy but to evaluate if GNSS positions from the built-in receiver aid in any way to the final deliverable. Still regarding [7], the iLiDAR data accuracy did not increase too significantly between Generation 1 to Generation 2 LiDAR and camera systems. Overall, relative accuracy is exceptionally low when compared to that of total station data or a comparison to what we have in laser scanners as for most results we may only attain <10 centimeter (cm) of accuracy. However, the iLiDAR point accuracy maintains at satisfyingly at <1cm at points close to the start as advertised as there still exists the same drift as the iPhone 12 which makes it incompatible and insufficient for mapping and even dangerous. To that point, however, we can supplement the iPhone data with correctly surveyed control points we can reduce this error such that one could say it is relatively accurate if we understand the results should be. The iPhone 13, a later model than iPhone 12, does hold its positional accuracy overall and their colorized point's works lines up neatly with the point cloud.

According to the numerous studies conducted for comparing two-point cloud datasets including [8,9,10] , a trend for a defined accuracy assessment procedure that mirrors the one initiated by [11](Gillihan, 2021) is evident. In a 2021 research paper conducted by [11](Gillihan, 2021), the suitability of the iLiDAR sensor for forensic work was interrogated. The researchers used three techniques for LiDAR comparison including a cloud-to-cloud comparison, a rudimentary comparison of tape measurements, and chalk outline clarity test. In the research conducted by [10](Ahmad Fuad et al., 2018), point cloud comparison using two different registration algorithms. Individual point clouds were aligned together in Cloud Compare and made use of the cloud-to-cloud distance model computations. According to [10](Ahmad Fuad et al., 2018), three-dimensional (3D) deviation analysis between point cloud is best performed using a cloud-to-cloud computation to provide for a comparison of the entire range of available points instead of a point-to-point or point-to-cloud method. In the research conducted by [9](Chauhan et al., 2021), two distinct distance models can be used: the Cloud-to-Cloud Comparison, Cloud-to-Cloud (C2C) Distance, and Multi Scale Model-to-Model (M2M) Cloud Comparison, Model-to-Model Cloud (M3C2) Distance. Based on literature the iLiDAR scans conducted using two different scanning method can be compared based on overlap they provide as well as an estimation of the drift seen in the data and how it manages elevation changes. This will allow the researchers to consider how diverse data collectors can conduct their work. The current study adopts C2C and M3C2 approaches in comparing the derived point clouds.

3.0 Material and Methods

The study area selected for this investigation was a modern building within Rondebosch, Cape Town, South Africa. The building was selected as regular but complex with several stairs and corridors was selected for the case at hand. To begin with consideration of the requirements around producing a concise scan and the characteristics that must also be weighed in were considered. The researchers reflected on the overall method of data capture to ensure that all necessary data would be collected optimally and in a state that makes it ready to use when preforming the analysis. The primary consideration towards selection of the building venue was also due to the iPhone 12 LiDAR scanner accommodation into the plan and limitations it may face with regards to the uncertainties it may be required to measure. From the preliminary literature research, it was concluded that the iPhone needed site characteristics consisting of: A combination of indoor and outdoor spaces, long corridors to inspect the effect of drift, varying lighting conditions ranging from very dark to bright, Inclusion of both varying and consistent elevation, accommodation of both short and medium scan ranges. Based on literature, it was also identified that the iLiDAR sensor is a LiDAR system boiled down to its simplest components, however, without all the correction mechanisms are available as seen in Trimble Laser Scanning systems. The researchers therefore opted to model the overall accuracy between point clouds, and monitor the effect due systematic errors, as make recommendations on how they can be corrected to meet the research aims. These above characteristics also need to be weighed with considerations to the sensitive nature of terrestrial laser scanner. The selected building therefore was found as ideal to both requirements. Figure 3 below captures some detail of the test site.

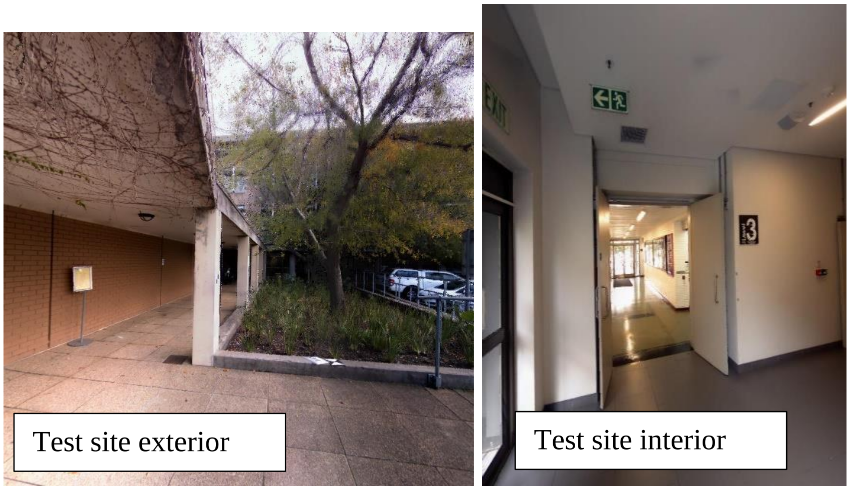

Figure 3: Sample images of Terrestrial Laser Scanner test site [Source: Own Compilation]

As highlighted above, to evaluate the integrity of the iPhone 12 LiDAR scanner it was compared to a terrestrial laser scanner point cloud (both a Trimble Laser scanner and Z and F scanner). The initial field step was to set up control points that would be a network guide for the tests. When establishing the control network, it was important to first plan out provisional scan position to ensure that there will be enough control in the system to minimize the errors and geo-referenced the scans. Two additional ground control points (GCPs) were placed outside of the test site and observed using Virtual Reference Station Real Time Kinematic (VRS RTK) GNSS due to limited nearby control and limited GNSS reliability in built up areas. To make a comparison of the scans and register the two LiDAR point clouds, targets were placed on the walls wherever possible. These targets were black and white as shown in Figure 4 and placed about 1.5 meters above the ground. Targets were not placed all around completely, because to whether conditions that day, and instead chose noticeable features like the edges of signs for the remaining segments of the building

Figure 4: Sample of Terrestrial Laser Scanner Targets placed on North wall

The Trimble X7 (TLS)and Z and F scanner allowed for a cloud-to-cloud registration which can be done in the field and therefore the relationship between scans and GCPs were not as vital, as in the methods of the past. Setup positions were chosen based on the desired amount of detail and overlap between scans as well as proximity to the available GCPs. Since the iPhone LiDAR needed to be on the same coordinate system as the laser point cloud for seamless comparison and to keep good positional accuracy for the iPhone during data capture, open source GNSS data was be used. Cleaning the data amounted to remove all unnecessary features from the point cloud such that only the building feature, paths and steps were accounted for ~~was conducted~~. This was to ensure that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. Using the field data for the iLiDAR scans, the researchers were able to produce a workable deliverable by following a similar workflow to that of mobile laser scanning due to the similarities in the data acquisition process. However, to add to this the process, the iLiDAR scans will also include a registration step as the scanning process was done per wall to reduce strain on the iPhone processing unite.

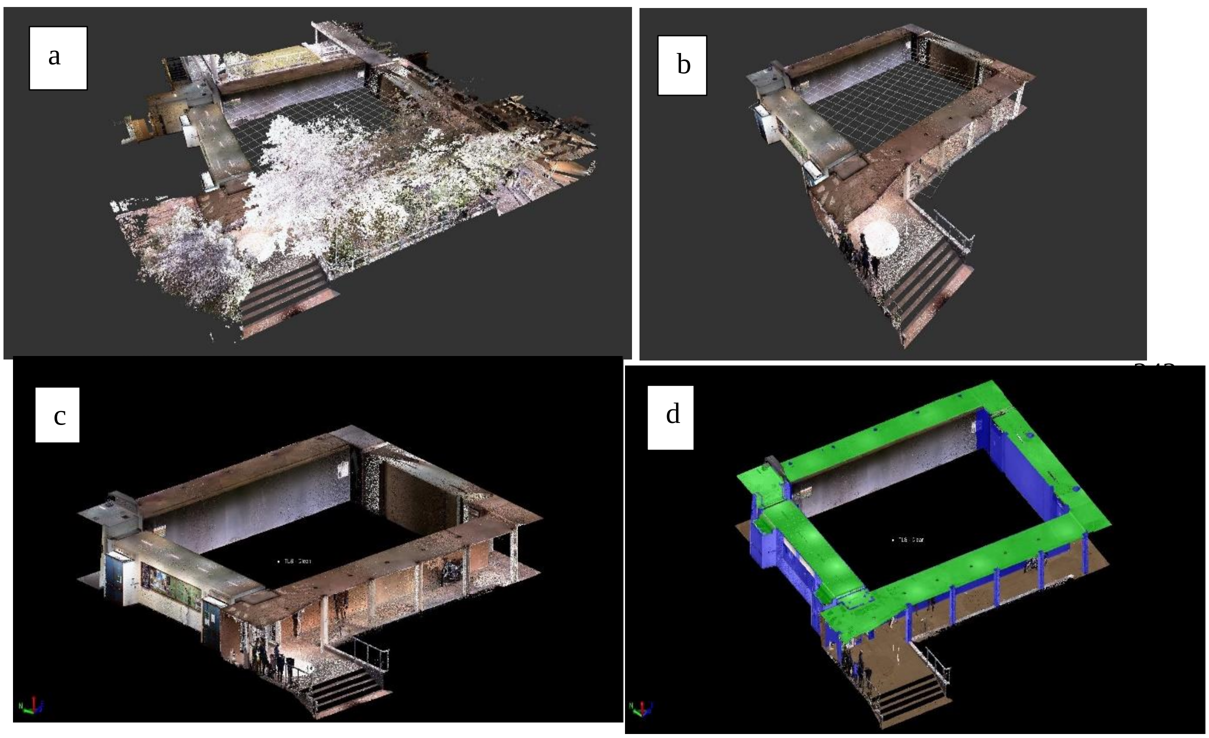

Figure 5: a) Uncleaned TLS point cloud; b) Cleaned TLS point cloud already geo-referenced; c) Cleaned TLS point cloud and d) Classified TLS point cloud loaded into [Source: Own Compilation]

A problem regarding the processing of the LiDAR data came with loading the raw data itself and its ease to import into the necessary post processing software. During the importing process the point clouds appeared to struggle to be interoperable with the software of choice, and if loaded the point cloud may either be extremely small or may disintegrate into an extensive line of points. A probable reason for this may be due to either the processing done by the A14 bionic chip within that may not be allowing the cloud to speak to the computer correctly or may also deal with the way the iPhone 12 formed the geo-referenced file. Another challenge was that since the iLiDAR could only have minimal overlap areas at the edges for each wall a least square adjustment solution would cause walls to be inverted in the opposite direction. This was because the matching algorithm views the maximum amount of area within the scans overlap region by tying in other similar features to one another. However, this causes the scan to be mirrored to one another so that the faces of the features are overlapped on top of one another orientated in the same direction. This in practice could be solved with an additional point at the end of the wall to keep the orientation of each scan defined. This meant that the iLiDAR scans would have to be aligned to the Trimble Laser Scanner (TLS) dataset so that the scans are aligned correctly. The iLiDAR cloud was orientated to the TLS cloud using a Rotate/Align function and was finely aligned using the Finely Align function to correct the remaining orientation discrepancies to overlay the two scans together. This effectively registered the two clouds together with the TLS cloud as a reference after 20 iterations and five thousand random point samplings. The aligned scans were merged into one point cloud for both the two meter (m) and 4m scans with the 4m scan containing the inside corridor. Since the inside corridor needed enough point to tie the scan into the remaining other scans it is integrated into the 4m scan. Though the scan could not have been done with a 4m scan range, this choice is justifiable as scanning was done using the maximum possible distance away from the object which is also. These merged scans were exported into Trimble Business Centre (TBC) to be classified and cleaned further.

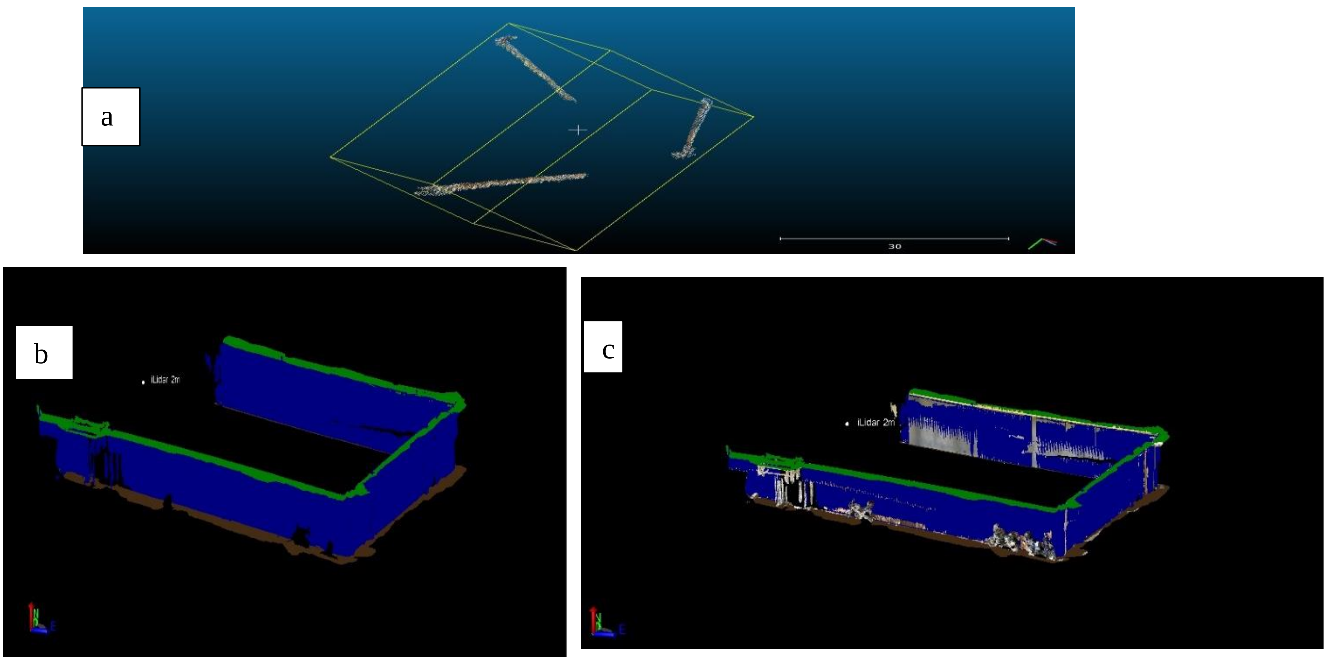

Figure 6: a) iLiDAR point clouds displaced due to GPS receiver capability b) Images of TLS and iLiDAR point cloud alignment in Cloud Compare for 2m scan c) Final Product – Classified 2m iLiDAR point cloud loaded into TBC

The TLS and iLiDAR dataset required further pre-processing to allow for an adequate model so to compute the accuracy of the generated iLiDAR scan and make inferences on it. The accuracy of the iLiDAR point cloud could now be evaluated by the researchers using visual interpretation and cloud to cloud (C2C) distance models as adopted from literature, which compute the distance between two respective points in a point cloud.

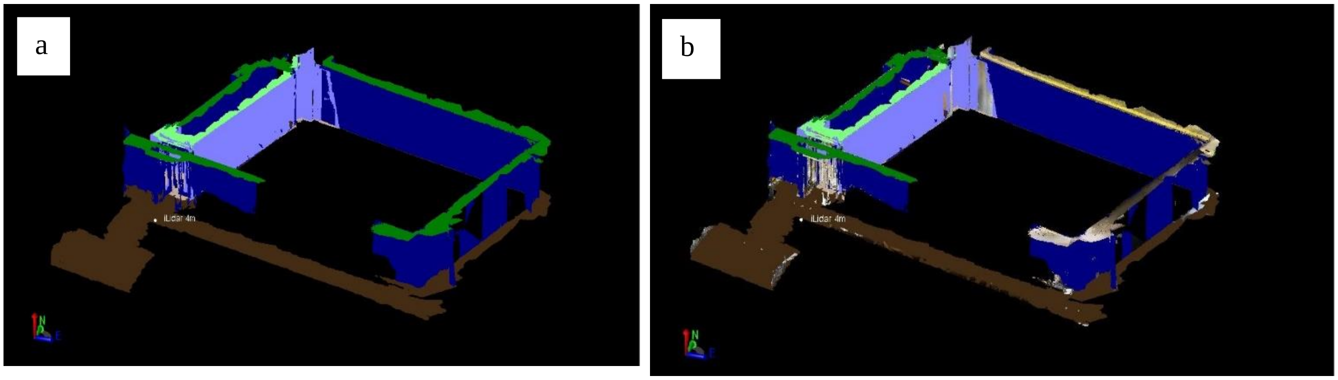

Figure 7: Images of TLS and iLiDAR point cloud alignment and cloud registration in Cloud Compare for 4m scan [Source: Own Compilation]

4.0 Results and Discussions

Regarding the cloud distance methods, the detection and removal of outliers was conducted using a python program. The results were summarized to highlight the change in centrality for each local model, providing insight into the skewness, concentration, and distribution of the data. The values used to remove outliers from the original point clouds were highlighted by the 'Outlier Bounds' entries and the effect of their use was monitored using the comparison table. Heat maps are the fundamental deliverables for each C2C Distance algorithm used, and demonstrated the product of the cloud-to-cloud distance computations post removal of outliers. Visual analysis of this data was summarized in descriptive statistics tables which gave an overall mean and 95% confidence interval for each scan. The products of the M3C2 Distance algorithms were also provided with its own corresponding tabulations and heat maps with respect to the C2C Distance method. All figures provided remained in a singular format across all cloud-to-cloud distance computations used in this research. The M3C2 provided distance comparisons and summaries for its own cloud distance computations and an analysis of the statistical models used for conveying the product's precision. The above-mentioned figures and comments are laid down for further interpretation. Preliminary evaluation of the percentiles showed that there is moderate agreement between models of how spread the data was, which also displays some repeatability between specific values. It must be noted that the lower bounds used for the removal of outliers extend into the negative direction which is not applicable for the C2C models which use absolute distances. Therefore, the lower bounds used in practice were in fact close to zero. Table 1 below highlights some of the percentiles of the C2C local model distance at 2m, compiled as results as described above. Table 2 on the other hand displays descriptive statistics of each C2C model at 2m. The removal of outliers using percentiles caused a change in accuracy of 1.3cm indicating that these are groups of large values, up to 60cm, in small proportions implying potential outliers removed. Evaluating the data across all the local models revealed that the relative accuracy of the iLiDAR repeats between six centimetres (cm) and 8cm, on average. All models show low variability with a SD fluctuating between 5.5cm and 7cm, with standard error measures close to zero implying that these averages are good estimators of the true mean. In addition, the 95%

confidence interval in each model allows for a 3mm window for its estimation of the true mean, implying strongly that these means closely approximate this value.

Table 1: Percentile table of C2C Local Model Distances used to evaluate outliers in 2m scan

Comparison of C2C Distance Local Model Percentile Tables (iLidar 2m)

Nearest Neighbour			Least Squares Plane			2D1/2 Triangulation			Quadric Height Function		
Percentile Table			Percentile Table			Percentile Table			Percentile Table		
		meters			meters			meters			meters
P10	10%	0.009	P10	10%	0.006	P10	10%	0.008	P10	10%	0.006
P20	20%	0.019	P20	20%	0.013	P20	20%	0.019	P20	20%	0.012
P25	25%	0.024	P25	25%	0.017	P25	25%	0.024	P25	25%	0.016
P50	50%	0.065	P50	50%	0.046	P50	50%	0.065	P50	50%	0.044
P75	75%	0.140	P75	75%	0.101	P75	75%	0.140	P75	75%	0.103
P90	90%	0.211	P90	90%	0.167	P90	90%	0.211	P90	90%	0.172
P95	95%	0.315	P95	95%	0.211	P95	95%	0.315	P95	95%	0.216
Outlier Bounds			Outlier Bounds			Outlier Bounds			Outlier Bounds		
Upper Bound		0.314	Upper Bound		0.229	Upper Bound		0.314	Upper Bound		0.233
Lower Bound		-0.150	Lower Bound		-0.110	Lower Bound		-0.150	Lower Bound		-0.115

Table 2: Descriptive statistics table of each C2C Local Model Distances in 2m scan

Summary Statistics of C2C Distance Local Model (iLidar 2m)

Nearest Neighbour		Least Squares Plane		2D1/2 Triangulation		Quadric Height Function	
Summary of Results		Summary of Results		Summary of Results		Summary of Results	
Mean (m)	0.080	Mean (m)	0.060	Mean (m)	0.080	Mean (m)	0.061
Standard Error (m)	0.00004	Standard Error (m)	0.00003	Standard Error (m)	0.00004	Standard Error (m)	0.00003
Mode (m)	0.003	Mode (m)	0.001	Mode (m)	0.003	Mode (m)	0.002
Median (m)	0.060	Median (m)	0.043	Median (m)	0.060	Median (m)	0.041
Standard Deviation (m)	0.070	Standard Deviation (m)	0.055	Standard Deviation (m)	0.070	Standard Deviation (m)	0.057
Sample Variance (m)	0.005	Sample Variance (m)	0.003	Sample Variance (m)	0.005	Sample Variance (m)	0.003
Range (m)	0.314	Range (m)	0.228	Range (m)	0.314	Range (m)	0.233
Maximum (m)	0.314	Maximum (m)	0.228	Maximum (m)	0.314	Maximum (m)	0.233
Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000

Points	3131245	Points	3165355	Points	3129841	Points	3160523
Sum (m)	250782.6	Sum (m)	190980.5	Sum (m)	250440.5	Sum (m)	191504.1
Classes	1770	Classes	1780	Classes	1770	Classes	1778
Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)	
Lower CI (m)	0.079	Lower CI (m)	0.059	Lower CI (m)	0.078	Lower CI (m)	0.059
Upper CI (m)	0.082	Upper CI (m)	0.062	Upper CI (m)	0.082	Upper CI (m)	0.062

However, additional indicators such as substantial range values of 23cm and 31cm with their respective SD values, needs further interpretation with respect to their Weibull distributions provided and the repeatability observed, to influence how we should interpret the M3C2 distance model.

C2C Distances - Local Model Methods (iLidar 2m)

Name	Points	meanX	meanY	meanZ	C2C Distance name	C2C Distance valid values	C2C Distance mean	C2C Distance std.dev.	C2C Distance sum
C2C Distances									
iLidar 2m (NN)	3296572	47.398	66.995	123.109	C2C absolute distances [Nearest Neighbor]	3296572	0.096	0.098	317080
iLidar 2m (LSP)	3296572	47.398	66.995	123.109	C2C absolute distances [Least Square Plane]	3296572	0.071	0.075	232432
iLidar 2m (Tri)	3296572	47.398	66.995	123.109	C2C absolute distances [2D1/2 Triangulation]	3295205	0.096	0.099	316749
iLidar 2m (QHF)	3296572	47.398	66.995	123.109	C2C absolute distances [Quadric]	3296534	0.072	0.080	237563
Overall iLidar 2m - C2C	3296572	47.398	66.995	123.109	C2C absolute distances	3296221	0.084	0.088	275956
C2C Distances - Outliers Removes									
								Meters	
iLidar 2m (NN)	3131245	47.882	67.207	123.136	C2C absolute distances [Nearest Neighbor]	3131245	0.080	0.070	250783
iLidar 2m (LSP)	3165355	47.752	67.161	123.129	C2C absolute distances [Least Square Plane]	3165355	0.060	0.055	190980
iLidar 2m (Tri)	3129841	47.882	67.207	123.136	C2C absolute distances [2D1/2 Triangulation]	3129841	0.080	0.070	250440
iLidar 2m (QHF)	3160523	47.760	67.173	123.129	C2C absolute distances [Quadric]	3160523	0.061	0.057	191504
Overall iLidar 2m - C2C	3146741	47.819	67.187	123.133	C2C absolute distances	3146741	0.070	0.063	220927
C2C Distances - Change									
						Meters		*Meters*	
iLidar 2m (NN)	165327	-0.484	-0.212	-0.027	C2C absolute distances [Nearest Neighbor]	165327	0.016	0.029	66297
iLidar 2m (LSP)	131217	-0.355	-0.166	-0.020	C2C absolute distances [Least Square Plane]	131217	0.010	0.020	41452
iLidar 2m (Tri)	166731	-0.485	-0.212	-0.027	C2C absolute distances [2D1/2 Triangulation]	165364	0.016	0.029	66309
iLidar 2m (QHF)	136049	-0.362	-0.178	-0.020	C2C absolute distances [Quadric]	136011	0.011	0.023	46059
	149831	-0.422	-0.192	-0.024	C2C absolute distances	149480	0.013	0.025	55029
Overall iLidar 2m - C2C									
					Percentage Change	4.53%	16.08%	28.62%	19.94%

Table 3: Comparison Table of C2C Local Model Distances before and after removal of outliers in 2m scan

Below are the final outputs of each C2C Distance local model used in the iLiDAR comparison for the 2m scan, with its scalar field color ramp on the right showing the color corresponding to the distance calculated and a 10m scale bar. The dataset shows the visual distributions of the departures across the object surface revealing the areas demonstrating the most and least variation from the TLS dataset. Red regions remain consistent between all local models; however, some models are more lenient with reporting the effect of these areas have on the data. The red areas within the nearest neighbour (NN) and Two-dimensional Triangulation (2DT) models have more missing data in these regions which indicate that these are the locations were most outliers were removed. The converse also remains true with regards to blue areas showing very stable results across all models having very dense point counts and show extraordinarily slight variation across all models such as the west wall. Areas of interest regarding larger error values include the north (front facing wall) entrance and its adjacent wall segments. These areas appear more speckled in the Least Squares Plane (LSP) and Quadratics Height Function (QHF) models with very random error responses ranging from exceptionally large, 22cm, and exceedingly small, close to zero. Within the local models these problem areas may be signs of erroneous inclusions and correspond to areas of large drift error. This means that since the survey of the building was performed in three smaller scans, our final 2m scan is not homogenous in terms of shape, orientation, and accuracy, therefore, each scan contributes uniquely to the overall model.

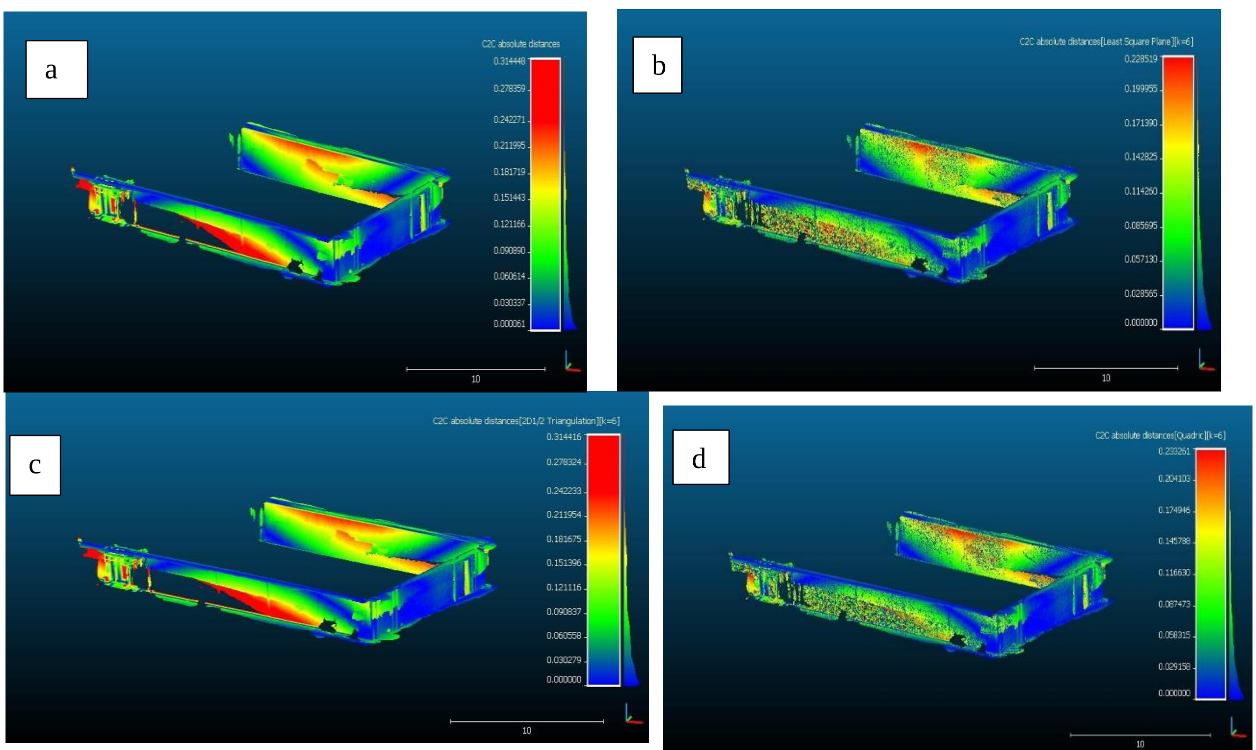

Figure 8: a) C2C Distance – Nearest Neighbour for 2m scan b) C2C Distance – Least Squares Plane for 2m scan c) C2C Distance – 2D ½ Triangulation for 2m scan d) C2C Distance – Quadratic Height Function for 2m scan with its scalar field ramp, scale bar and orthogonal axes [Source: Own Compilation]

In the results of the above methodology, the researchers aimed to evaluate whether the factors of our initial hypothesis on the comparison of accuracies of iLiDAR with commercial scanners would coincide with what we observed in the field. A cloud-to-cloud distance assessment provides for an approximation of the iLiDAR accuracy using descriptive statistics providing different averages for the distance discrepancies giving a general idea of what the system can give a 95% confidence. In addition, the use of the root mean square (RMS) and Chi-squared results give a final estimate of the average error observed and showed how well the data can be modelled. Results provides a comparison of distances across the 2m and 4m datasets to evaluate if the scanning method yields contrary results to the hypothesis or reasserts them. Upon visual inspection of the cloud datasets, all point clouds showed significant departures and large segments of discontinuity in the iLiDAR clouds. These areas marked out in red are instances of drift. However, as a general summary, the iLiDAR seemed to approximate the TLS dataset well, specifically within the 4m scan. of the data in the negative direction and are representing points behind the wall which cannot be possible. This gave more credence that the lenient local models which produce more noise are utilizing erroneous inclusions into its computations. Regarding the 4m scan, it could be seen that there was more uniformity between all four local models which is indicative that there are less outliers due to drift within the scan. Mean and standard deviation (SD) values as well as the indicators of well estimated mean, were all much more precise in their estimation than compared to the 2m scan. For each local model, the data conveyed that the best estimate of the mean using that algorithm is only 1mm different from the true mean. This did not imply that the population mean for the iLiDAR scan as reported in these tables is 1mm away from these estimates, but it reported on the confidence we have in mean computed for that specific algorithm.

Since the 4m scan outperformed the 2m in such a way, it implied that the 4m provides the more authentic estimation of the accuracy available to the iLiDAR. This is seen by considering the descriptive statistics tables to their Weibull distribution, the beta values, *b*, have decreased from about 0.8 – 0.6, to 0.33 – 0.26 which means there was more conformity in terms of a lack of reliability to reach the larger error values in the 4m scan than in the 2m. Within the 2m scan, it was addressed that due to this the noisier local models must come into further evaluation because it was known that it is wrong to assume lower reliability to reach larger values in these areas because we know that the iLiDAR skewed because of drift. However, in the 4m scan there was more agreement between the models, and though the reliability on achieving larger values has decreased, we are more trustworthy of this assessment since we observe less drift errors. In addition, because of the scale, and shift parameters it was seen that the reliability was more defined over its error classes which implies that the Weibull distribution is reporting on the full scope of the errors possible and not understating the effect of the larger errors. It must also be noted that the minimum value for each local model is not exactly zero meaning that the iLiDAR is not precisely synchronous with the TLS dataset but that based on the local model used it very closely approximates our TLS in these areas. This was seen as we expand the values to further decimal places and see the residual error in the iLiDAR measurements. However, these small errors were submillimeter which are not measureable in practice and thus the exact value could not be used. Based on data long scan lines only increased the chance of misalignment due to drift. A possible reason for this relation between scan length and misalignment was due to a decreased potential for overlap during the scanning process as longer scan lines make the iLiDAR scan more dependent on maintaining good IMU capability i.e., longer scan lines needed a very good fix on its orientation and position in space than shorter scans, in addition to less available area for overlap. It must be carefully noted that it is a lack of overlap in conjunction with the limit IMU ability of the iPhone that produces these errors. This is reciprocated in the areas within the 4m scan which had shorter scans lines but much more stable deliverables since a 4m scan will have a larger scope of the object being scanned there will be greater opportunity for overlap. This was therefore the primary reason that the 2m scan failed many to reach higher accuracies in comparison to the 4m scan.

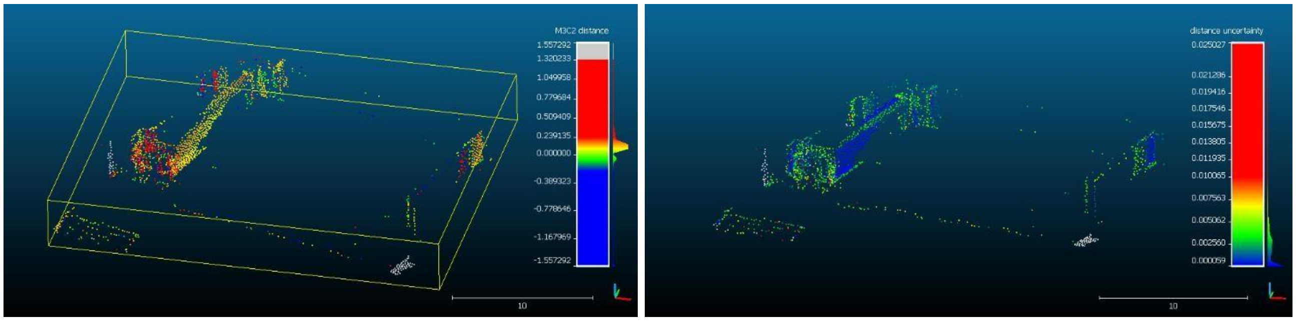

Figure 9: Diagram showing distance errors close to zero in 2m scan [Source: Own Compilation]

A reason for the iLiDAR's proclivity for sufficient overlap may be due to the algorithm ~~to~~ which the iPhone App, 3D Scanner and others, employs. This may be due to the knowledge of the mechanisms used in photogrammetric surveys and statistical theory used by the app developers. This is such that since the iLiDAR sensor has extremely limited ability to send out and capture laser pulses a way for a system such as this to maximize the available points and improve accuracy through redundant observations would benefit well from an algorithm that relies on overlap. A note to consider, was that as the researchers were gathering data, they noticed large pixels redistributing themselves when there is large overlap ~~was~~ occurring. This ~~in fact~~ corresponded to areas within the 4m scan which has a discrepancy of less than 1cm from the TLS dataset. There also seemed to be a threshold to which overlap can improve one's results as the nature of the object physical properties still play its role. The improvement between the 2m and 4m scans was still impressive moving from 8cm to 3cm with standard deviation decrease from 7cm to 2.2cm. An analysis of the 4m scan shows clear struggle for the iLiDAR due to the reflectivity of the surfaces for the north entrance. Braces for the doorframes were clearly displaced in the 2m scan showing that the IMU capability was not suited for long scan lines.

5.0 Conclusions and recommendations

The aim of this study is to evaluate the accuracy that the iPhone 12 Pro LiDAR scanner with its GNSS positions with respect to commercial grade point clouds. We see from the above results that the iLiDAR performed well for a fit for purpose too. However, it can be noted for highly accurate work that its GNSS capability not only failed to provide adequate absolute accuracy as anticipated, but it did not aid at all with maintain good iLiDAR measurement capability as seen in MLS. To address the possible methods of providing optimal results from the iLiDAR system, it is with strong recommendation that a proper stabilizer be used for the acquisition of the iLiDAR if greatest accuracy is desired. This would allow the IMU capabilities of the iPhone to work optimally with the SLAM algorithm in addition may also benefit from an external GNSS receiver. The researchers also recommend a look for a more integrated approach with structure from motion photogrammetry to reinforce the short comings of the iLiDAR system which may provide the near 1cm accuracy claimed by Apple developers.

6.0. Acknowledgements

[anonymised]

7.0 Conflict of interest

The authors declare no conflict of interest

8.0 Author contributions

[anonymised]

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Appendix 2: Reviewer B comments on manuscript

MOBILE PHONE BASED LiDAR AS A LOW-COST ALTERNATIVE FOR MULTI-DISCPLINARY DATA COLLECTION

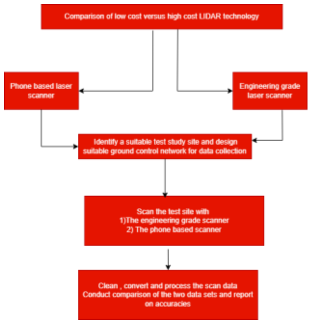
Abstract

Airborne and terrestrial laser scanning have traditionally been used as specialised toolsets for scene capture in engineering, providing highly accurate measurements with minimal human interaction. However, the commercial grade of these instruments remains expensive and sensitive, requiring costly routine calibrations to ensure their optimum functionality. The recent inclusion of a laser scanning sensor by mobile phone manufacturers such as Apple is now analogous to the integration of the ~~global~~ Global ~~navigation~~ Navigation ~~satellite~~ Satellite ~~systems~~ Systems (GNSS) and cameras into phones decades ago. , It is likely that these initial efforts to include the scanning sensor in mobile phones will see rapid improvements in the application and accuracy of the sensor to serve the growing need of scanning data for transdisciplinary users. However, there is a limited amount of literature that benchmarks emerging and low-cost scanning sensors to existing commercial ones to inform practise, thus prompting a need for researchers to evaluate and provide scientific evidence that can inform multi-disciplinary scanning practises. The researchers, therefore, investigated the extent to which laser scanning tools available within the iPhone 12 Pro compared to the engineering grade laser scanner. Outcomes from the research showed that iPhone scanners can deliver the required models albeit being relatively unstable when pitched against traditional LiDAR scanners. It was also noted that there was some positional shift and scan drift in the data. The research recommends that stabilizers such as gimbals or enhanced GNSS receivers, could be in used in practice to achieve improved accuracy from the mobile phone (iPhone) LiDAR.

Keywords: Multidisciplinary, Mobile Technologies, Laser Scanning, accuracy, low-cost, iLiDAR, sustainable solutions

Significance: Low-cost tool for curating models in three dimensions; Fit for approach purpose in multi-disciplinary science

Graphical Abstract



Introduction, Background and Aims

Light ~~detection~~ Detection and ~~ranging~~ Ranging (LIDAR) scanning systems have over the years allowed users to create observations of any man made or environmental structure for application in hundreds of areas such as geology, archaeology, engineering, and spatial data collection. [1] Airborne and terrestrial scanning methods provide of quick and accurate multi-point positional data capture at increased rates and this approach serves multiple users across the technical context of aerial (ALS), mobile (MLS) and terrestrial laser scanning (TLS) applications [1, 2]. Furthermore, terrestrial laser scanning using high grade equipment provides large volumes of point cloud data with high resolution for topographic mapping, meteorology, archaeology, monitoring deformation, building construction and structure analysis in engineering surveys [1]. These numerous applications have led rapid developments in mechanical and data processing capabilities attempting to make the systems more accurate, efficient, and affordable to a larger market. Recent applications have also extended to various other sciences and arts where physical models are of interest including health sciences, architecture, biodiversity, and many others [3]. However, access to scanning services has remained a barrier to broad application due to the high costs associated with commercial scan equipment and its maintenance plans. Since 2007, when the first iPhone was announced, there has been an increase in similar high-end mobile phone interfaces that have claimed to revolutionize many professional disciplines, by offering mass integration of distinguishable technologies with varied purposes, into mobile devices [5]. The rise in popularity of Apple's iPhone is driven by its constant innovations and out of the box utilities [6]. Of recent, Apple's ambition to improve themselves has led to the inclusion of their first (1st) Generation LiDAR (hereinafter referred to as iLiDAR) sensor incorporated into their new iPad Pro and iPhone 12 Pro models and devices beyond up to the more recent iPhone 15. The incorporation of this LiDAR sensor into the phone was intended at improving their Measure Application (app) capabilities by introducing depth sensing, portrait image capability, night mode performance, and Augmented and Virtual video game functionality [6]. It is therefore interesting to benchmark these lower cost sensors to engineering grade. Engineering grade laser scanners are specialized equipment to attain spatial data effectively and accurately, however, at a prohibitive cost of R600,000 to R2,000,000, in addition to routine maintenance to ensure its delivered accuracy. The iPhone 12 Pro and later models costing above R20,000, now provides LiDAR capabilities to the public which claim to provide comparable results, requiring no routine maintenance and offers real time processing. Literature posits that there is insufficient scientific knowledge on the iLiDAR capabilities as there are very few studies that have captured the gains of this recent development from an accuracy perspective [6,9,10]. The problem therefore lies in the limited amount of literature that benchmarks emerging and low-cost LiDAR sensors to existing commercial ones. There is therefore a need for researchers to evaluate and provide evidence that can assist users who may need to use the technology for various applications. This paper aims to test the accuracy of the iPhone's LiDAR sensor and its capabilities with respect to terrestrial laser scanner derived point clouds. The researchers investigated the extent to which an iPhone LiDAR tools available within the iPhone 12 Pro, compares to the engineering grade laser scanner. Monitoring how different technologies are being

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Commented [R4]: https://www.researchgate.net/profile/Sara-Shirowzhan/publication/320169091_Challenges_and_Opportunities_for_Implementation_of_Laser_Scanners_in_Building_Construction/links/5b21079a0f7e9b0e373fa0d1/Challenges-and-Opportunities-for-Implementation-of-Laser-Scanners-in-Building-Construction.pdf incorporated into existing technologies and how fast they grow in complexity will give an insight into the accuracy available for future data collection options.

Associated theories and literature review on advances in laser scanning technologies.

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Several models and frameworks have been developed to explain the user adoption of new technologies with more than one theoretical approach required for a complete understanding of trends in technology. In this paper, adoption theories and models are not significant. However, but due to the practical nature of the findings, which may get dated quickly, with the rapid advances in improved iPhone LiDAR or the sales of other lower-cost LiDAR devices, it is of value to highlight that technology adoption theories explain the changes and growth in development of low-cost devices in the literature. Moving over to the case of the LiDAR sensor in the iPhone mobile gadget, third party applications (apps) capitalized on the opportunity to use this LiDAR system in conjunction with the processing power of its new bionic core, to provide 3D models just as terrestrial LiDAR systems would [3,6]. The three-dimensional (3D) models appealed to multiple disciplines who could use the iLiDAR for reality capture and documentation. Therefore, the additional ability to reconstruct 3D models using the iLiDAR is not accredited to Apple, but several third-party sources who developed these apps to take advantage of the LiDAR system using the app developer's designed algorithm[1]. These sensors' function offers the same scientific concepts as their professional grade counterparts albeit reduced to the most basic components. These apps can produce well textured models through use of a simultaneous localisation and mapping (SLAM) algorithm, which in practice allows for the construction of maps and models through the continuous updating of results using precise determinations of the scanner's location and orientation [11]. This algorithm is used primarily for mobile laser scanning (MLS), as the LiDAR scanner is mounted to some vehicle with the Global Navigation Satellite System (GNSS) and Inertial Measurement nit (IMU) systems constantly keeping track of the vehicle during acquisition, where the SLAM algorithm allows for a registration and geo-referencing of all these points [3]. In the research done by (Luetzenburg, Kroon & Bjørk, 2021), [6], the accuracy of the iLiDAR systems is quoted to fluctuate between 3cm and 6cm, which demonstrates a high potential for the mapping of small-scale scenes such as residential rooms above. Apart from its use in gaming these capabilities are promising for forensics, real estate, physics, archaeology, and engineering documentation. Despite the rapid growth to increase reach, the addition of these added specialised competences to selected mobile phone would require immense focus on obtaining accurate measurements in real time, and with consideration that professional scanners require maintenance to provide quality data. The measurement principles behind LiDAR scanning are to juxtapose the numerous benefits and applications of the technology, sharing similar base concept of electronic distance measurements. LiDAR is at its core is a range detection method using a laser pulse to illuminate an object and measuring the time taken for this pulse to return to the source allowing the LiDAR scanner to accurately measure the distance between the sensor and the object. From the interaction of the laser pulse with an environment a three-dimensional impression of the

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[1] https://www.apple.com/newsroom/2020/03/apple-unveils-new-ipad-pro-with-lidar-scanner-and-trackpad-support-in-ipados/

real world is recreated with a collection of X, Y and Z coordinates for multiple locations. LiDAR sensing under low light condition providing overall accuracies of 0.191 metres (m), 0.242m, 0.345m at 20m, 40m, 60m altitudes [7]. Commercial terrestrial and mobile can achieve an accuracy of less than 20 millimetres (mm) for Time of Flight (TOF) scanners and less than 10mm for phase difference scanner [7]. It should be noted that this is a very general estimate due to the wide range of LiDAR scanners available on the market, as many can provide between 3mm and 6mm accuracies. Mobile laser scanning takes the concept of terrestrial or ground-based laser scanning but by adding a real time kinematic GNSS and inertial measurement unit (IMU) systems for a moving platform. This allows scanning to take place in rapid succession by driving a LiDAR scanner mounted to a vehicle/platform and producing a geo-referenced point cloud through registration.

The iPhone LiDAR (iLIDAR) scanner on the other hand is a combination of model sensors that provides users with the potential to approximate engineering grade mapping capabilities, as it combines a refined GNSS receiver, enhanced gyroscope, and accelerometer sensor as well as what is described as a high precision camera sensors and LiDAR sensor. In the research done by [8] (Tavani et al., 2022), the author described the iPhone 12 Pro LiDAR system as a paradigm shift, improving the geospatial data acquisition process through acquiring three-dimensional (3D) reconstruction models for fieldwork in real time. The study resonates with related work and posits that such a capability in the hands of scientist, such as geologists, would improve research fieldwork opportunities by increasing access to low-cost LiDAR data, and enhancing repeatability and transparency [3,5,6]. It is possible to add location or GNSS capability using the iPhone 12 Pro GNSS receiver, however, due to the low resolution available to these sensors, absolute accuracy will not approach engineering grade standards. However, in a study conducted by [10] (Tamimi, 2022), they concluded that the use of an external RTK GNSS receiver connected to the iPhone 12 via Bluetooth, may provide much higher accuracies by using much more defined positional information. It is, therefore, the purposes of this research to evaluate whether the same is true without the RTK receiver, not to evaluate absolute accuracy but to evaluate if GNSS positions from the built-in receiver aid in any way to the final deliverable. Still regarding [10] (Tamimi, 2022) the iLiDAR data accuracy did not increase too significantly between Generation 1 to Generation 2 LiDAR and camera systems. Overall, relative accuracy is exceptionally low when compared to that of total station data or a comparison to what we have in laser scanners as for most results we may only attain <10centimeter (cm) of accuracy. However, the iLiDAR point accuracy maintains at satisfyingly at <1cm at points close to the start as advertised as there still exists the same drift as the iPhone 12 which makes it incompatible and insufficient for mapping and even dangerous. To that point, however, we can supplement the iPhone data with correctly surveyed control points we can reduce this error such that one could say it is relatively accurate if we understand the results should be. The iPhone 13, a later model than iPhone 12, does hold its positional accuracy overall and their colorized point's works lines up neatly with the point cloud.

According to the numerous studies conducted for comparing two-point cloud datasets including [7](Santise et al., 2018), [12] (Chauhan et al., 2021), and [13](Ahmad Fuad et al., 2018), a trend for a defined accuracy

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assessment procedure that mirrors the one initiated by [14](Gillihan, 2021) is evident. In the work conducted by [14] (Gillihan, 2021), the suitability of the iLiDAR sensor for forensic work was interrogated. The researchers used three techniques for LiDAR comparison including a cloud-to-cloud comparison, a rudimentary comparison of tape measurements, and chalk outline clarity test. In similar work conducted by [13](Ahmad Fuad et al., 2018), point cloud comparison using two different registration algorithms. Individual point clouds were aligned together in Cloud Compare and made use of the cloud-to-cloud distance model computations. According to [[13](Ahmad Fuad et al., 2018), three-dimensional (3D) deviation analysis between point cloud is best performed using a cloud-to-cloud computation to provide for a comparison of the entire range of available points instead of a point-to-point or point-to-cloud method. In the research conducted by [12] (Chauhan et al., 2021), two distinct distance models can be used: the Cloud-to-Cloud Comparison, Cloud-to-Cloud (C2C) Distance, and Multi Scale Model-to-Model(M2M) Cloud Comparison, Model-to-Model Cloud (M3C2) Distance. Based on literature [11] the iLiDAR scans conducted using two different scanning method can be compared based on overlap they provide as well as an estimation of the drift seen in the data and how it manages elevation changes. This allowed the researchers to consider how diverse data collectors can conduct their work. The current study adopts C2C and M3C2 approaches in comparing the derived point clouds due to its statistical robustness that makes it reliable and scientifically sound in tests.

Material and Methods

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Cape Town is on South Africa's southwestern coast close to the Cape of Good Hope and is the southernmost city on the African continent The study site selected for this investigation was a modern building within Rondebosch, Cape Town, South Africa. The Snape and Menzies buildings[2] were selected as they presented regular but complex shapes with several stairs and corridors that are ideal for robust testing for the case at hand. It is important to highlight for ethical considerations that the authors have obtained ethical clearance to conduct the work and have no link with Apple. Tt the device is selected as it is one of the few mainstream mobile technologies at present that have introduced scanning technology, something that directly intersects with the researcher's line of work, it is for this reason that the iPhone LiDAR made a good candidate for further investigation. The researchers reflected on the overall method of data capture to ensure that all necessary data would be collected optimally and in a state that makes it ready to use when preforming the analysis. The primary consideration towards selection of the building venue was also due to the iPhone 12 LiDAR scanner accommodation into the plan and limitations it may face with regards to the uncertainties it may be required to measure. To kick off data collection, the initial field step was to set up control points that would be a network guide for the tests. When establishing the control network, it was important to first plan

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2 https://uct.ac.za/contacts-maps/buildings-departments-and-offices

out provisional scan position to ensure that there will be enough control in the system to minimize the errors and geo-referenced the scans. Two additional ground control points (GCPs) were placed outside of the test site and observed using Virtual Reference Station Real Time Kinematic (VRS RTK) GNSS due to limited nearby control and limited GNSS reliability in built up areas. As highlighted above, to evaluate the integrity of the iPhone 12 LiDAR scanner it was compared to a terrestrial laser scanner point cloud (both a Trimble Laser scanner and Z and F scanner). To make a comparison of the scans and register the two LiDAR point clouds, targets were placed on the walls wherever possible. These targets were black and white markers and were placed about 1.5 meters above the ground. Targets were not placed all around completely, because to whether conditions that day, and instead chose noticeable features like the edges of signs for the remaining segments of the building. The Trimble X7 (TLS)and Z and F scanner allowed for a cloud-to-cloud registration which can be done in the field and therefore the relationship between scans and ground control points (GCPs) were not as vital, as in the methods of the past. Setup positions were chosen based on the desired amount of detail and overlap between scans as well as proximity to the available GCPs. Since the iPhone LiDAR needed to be on the same coordinate system as the laser point cloud for seamless comparison and to keep good positional accuracy for the iPhone during data capture, open source GNSS data was be used. Thereafter cleaning of the data which amounted to removing all unnecessary features from the point cloud was conducted. This was to ensure that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. Once the data was ready, the two datasets from the terrestrial scanner and the phone scanner were further processed and compared to highlight similarities and key differences. An accuracy-based approach to the comparison was adopted using algorithms within Cloud Compare. Cleaning the data amounted to remove all unnecessary features from the point cloud such that only the building feature, paths and steps were accounted for was conducted. This was to ensure that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. Using the field data for the iLiDAR scans, the researchers were able to produce a workable deliverable by following a similar workflow to that of mobile laser scanning due to the similarities in the data acquisition process. However, to add to this the process, the iLiDAR scans will also include a registration step as the scanning process was done per wall to reduce strain on the iPhone processing unite.

Results and Discussions

Using the field data for the iLiDAR scans, the researchers were able to follow a similar workflow to that of processing mobile laser scanning (MLS) due to the similarities it holds with the iLiDAR data acquisition process. However, to add to this the process, the iLiDAR scans also required a registration step as the scanning process had to be done per wall to reduce strain on the iPhone processing unit. Thereafter, cleaning the collected data involved removing all unnecessary features from the point cloud such that only the building feature, paths and steps were accounted (Figure *1*~~Figure 1~~). This was to ensure that the cloud has the same features as the iLiDAR

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Commented [R14]: Is this not methodology (what you did) - it cant be part of the results point cloud must enable a correct comparison between these two datasets. During the importing process the iLIDAR point clouds appeared to struggle to be interoperable with the software of choice, and when loaded the point cloud would either be extremely small or disintegrate into an extensive line of points. A probable reason for this may be due to either the processing done by the A14 bionic chip within that may not be allowing the cloud to communicate to the computer correctly or may also deal with the way the iPhone 12 formed the geo-referenced file. This was as expected and seen with many Apple devices where compatibility with other platforms may not always be smooth.

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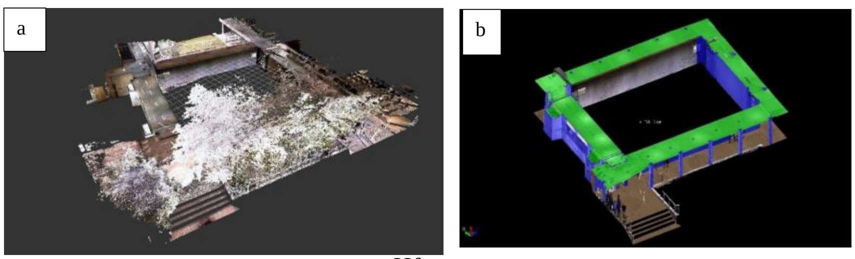

Figure 1: a) Uncleaned Trimble Laser Scanner (TLS) point cloud; b) Cleaned and classified TLS point cloud

After cleaning some further inspection of the data followed. Another challenge identified was that since the iLiDAR could only have minimal overlap areas at the edges for each wall, a least square adjustment matching solution would cause walls to be inverted in the opposite direction. This was because the matching algorithm views the maximum amount of area within the scans overlap region by tying in other similar features to one another. However, this would cause the scan to be mirrored to one another so that the faces of the features are overlapped on top of one another orientated in the same direction. This in practice could be solved with an additional point at the end of the wall to keep the orientation of each scan defined. This meant that the iLiDAR scans now had to be aligned to the Trimble Laser Scanner (TLS) dataset so that the scans were aligned correctly. The iLiDAR cloud was then orientated to the TLS cloud using a Rotate or Align function and it was finely aligned using the Finely Align function to correct for the remaining orientation discrepancies and overlay the two scans together. This effectively registered the two clouds together with the TLS cloud as a reference after 20 iterations and five thousand random point samplings. The aligned scans were merged into one point cloud for both two meter (m) and 4m scans. The 4m scan contained the inside corridor. Since the inside corridor needed enough points to tie the scan into the remaining other scans it was integrated into the 4m scan. Though the scan could not have been done with a 4m scan range, this choice is justifiable as scanning was done using the maximum possible distance away from the object. These merged scans were exported into Trimble Business Centre (TBC) to be classified and cleaned further. The accuracy of the iLiDAR point cloud could now be evaluated further by the researchers, using visual interpretation and cloud to cloud (C2C) distance models as adopted from literature, which compute the distance between two respective points in a point cloud. Regarding the cloud distance methods, the detection and removal of outliers was firstly conducted using a python program. The results were summarized to highlight the change in centrality for each local model, providing insight into the skewness, concentration, and distribution of the data. Visual analysis of this data was summarized in descriptive statistics tables which gave an overall mean and 95% confidence interval for each scan. The products of the M3C2 Distance algorithms were also provided with their own corresponding tabulations and heat maps with respect to the C2C Distance method. The M3C2 provided distance comparisons and summaries for its own cloud distance computations and an analysis of the statistical models used for conveying the product's precision.

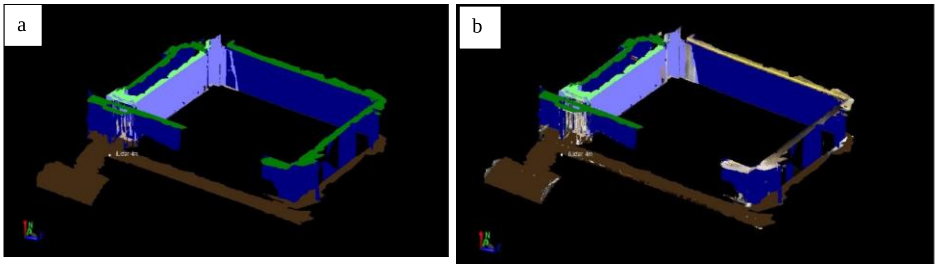

Figure 2 Images of a) TLS and b) iLiDAR point cloud alignment and cloud registration in Cloud Compare for 4m scan.

Table *1*: ~~Table 1 shows descriptive statistics table of each C2C Local Model Distances in 2m scan~~ .

Table 1: Summary Statistics of C2C Distance Local Model (iLidar 2m)

Nearest Neighbour		Least Squares PlanE		2D1/2N Triangulation		Quadric Height Function	
Summary of Results		Summary of ResultS		Summary of ResultS		Summary of Results	
Mean (m)	0.080	Mean (m)	0.060	Mean (m)	0.080	Mean (m)	0.061
Standard Error (m)	0.00004	Standard Error (m)	0.00003	Standard Error (m)	0.00004	Standard Error (m)	0.00003
Mode (m)	0.003	Mode (m)	0.001	Mode (m)	0.003	Mode (m)	0.002
Median (m)	0.060	Median (m)	0.043	Median (m)	0.060	Median (m)	0.041
Standard Deviation (m)	0.070	Standard Deviation (m)	0.055	Standard Deviation (m)	0.070	Standard Deviation (m)	0.057
Sample Variance (m)	0.005	Sample Variance (m)	0.003	Sample Variance (m)	0.005	Sample Variance (m)	0.003
Range (m)	0.314	Range (m)	0.228	Range (m)	0.314	Range (m)	0.233
Maximum (m)	0.314	Maximum (m)	0.228	Maximum (m)	0.314	Maximum (m)	0.233
Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000
Points	3131245	Points	3165355	Points	3129841	Points	3160523
Sum (m)	250782.6	Sum (m)	190980.5	Sum (m)	250440.5	Sum (m)	191504.1
Classes	1770	Classes	1780	Classes	1770	Classes	1778

Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)	
Lower CI (m)	0.079	Lower CI (m)	0.059	Lower CI (m)	0.078	Lower CI (m)	0.059
Upper CI (m)	0.082	Upper CI (m)	0.062	Upper CI (m)	0.082	Upper CI (m)	0.062

The removal of outliers using percentiles caused a change in accuracy of 1.3cm indicating that these are groups of large values, up to 60cm, in small proportions implying that potential outliers were removed. Evaluating the data across all the local models revealed that the relative accuracy of the iLiDAR was between six centimetres (cm) and 8cm, on average. All models showed low variability with a standard deviation (SD) fluctuating between 5.5 and 7), and standard error measures close to zero implying that these averages are good estimators of the true mean. In addition, the 95% confidence interval in each model allowed for a 3mm window for its estimation of the true mean, implying strongly that these means closely approximate this value. The final outputs of each C2C Distance local model used in the iLiDAR comparison for the 2m scan, were also prepared with its scalar field colour ramp as illustrated in Figure 3 , showing the colour corresponding to the distance calculated and a 10m scale bar. The dataset showed the visual distributions of the departures across the object surface revealing the areas demonstrating the most and least variation from the TLS dataset.

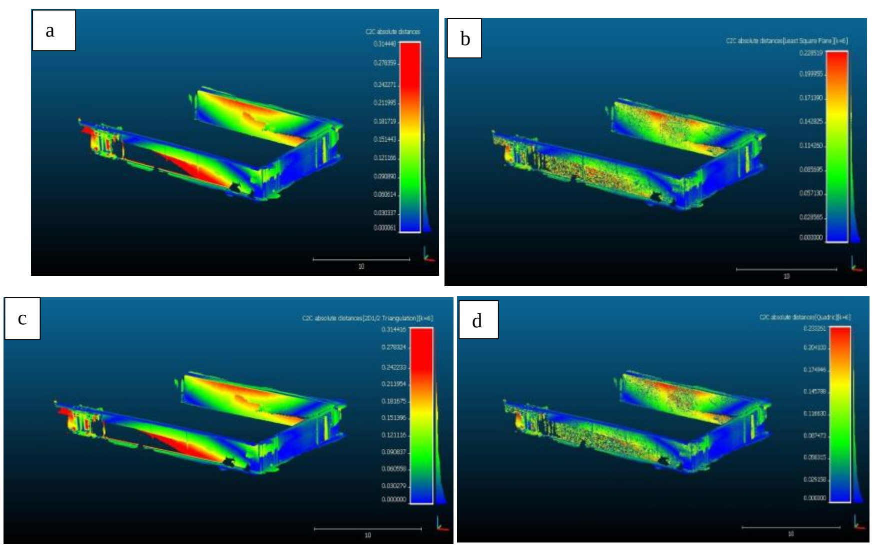

Figure 3 *a) C2C Distance – Nearest Neighbour for 2m scan b) C2C Distance – Least Squares Plane for 2m scan c) C2C Distance – 2D ½ Triangulation for 2m scan d) C2C Distance – Quadratic Height Function for 2m scan with its scalar field ramp, scale bar and orthogonal axes*

Red regions on heatmaps, remained consistent between all local models; however, some models are more lenient with reporting the effect of these areas have on the data. The red areas within the nearest neighbour (NN) and Two-dimensional Triangulation (2DT) models have more missing data in these regions which indicate that these are the locations were most outliers were removed. The converse also remains true with regards to blue areas showing very stable results across all models having very dense point counts and show extraordinarily slight variation across all models such as the west wall. Areas of interest regarding larger error values include the north (front facing wall) entrance and its adjacent wall segments. These areas appear more speckled in the Least Squares Plane (LSP) and Quadratics Height Function (QHF) models with very random error responses ranging from exceptionally large, 22cm, and exceedingly small, close to zero. In the results of the above methodology, the researchers aimed to evaluate whether the factors of our initial view on the comparison of accuracies of iLiDAR with commercial scanners would coincide with what we observed in the field. A cloud-to-cloud distance assessment provided for an approximation of the iLiDAR accuracy using descriptive statistics providing different averages for the distance discrepancies giving a general idea of what the system can give a 95% confidence. In addition, the use of the root mean square (RMS) and Chi-squared results give a final estimate of the average error observed and showed how well the data can be modelled. Results provided a comparison of distances across the 2m and 4m datasets to evaluate if the scanning method yields contrary results to the view or reasserts them. Upon visual inspection of the cloud datasets, all point clouds showed significant departures and large segments of discontinuity in the iLiDAR clouds. However, as a general summary, the iLiDAR seemed to approximate the TLS dataset well, specifically within the 4m scan. of the data in the negative direction and represented points behind the wall which could not have been possible. This gave more credence that the lenient local models which produce more noise are utilizing erroneous inclusions into its computations. For each local model, the data conveyed that the best estimate of the mean using that algorithm is only 1mm different from the true mean. This did not imply that the population mean for the iLiDAR scan was 1mm away from these estimates, but it reported on the confidence we have in mean computed for that specific algorithm.

Since the 4m scan outperformed the 2m in this manner, it implied that the 4m provides the more authentic estimation of the accuracy available to the iLiDAR. This was further seen by considering the descriptive statistics tables to their Weibull distribution, where beta values, *b*, decreased from about 0.8 – 0.6, to 0.33 – 0.26 which meant that there was more conformity in terms of a lack of reliability to reach the larger error values in the 4m scan than in the 2m. Within the 2m scan, it was noted that due to this the noisier local models had to come into further evaluation because it was known that it is wrong to assume lower reliability to reach larger values in these areas as we know that the iLiDAR skewed because of drift. However, in the 4m scan there was more agreement between the models, and though the reliability on achieving larger values has decreased, there was more trust in this assessment since we observe less drift errors. In addition, because of the scale, and shift parameters it was seen that the reliability was more defined over its error classes which implies that the Weibull distribution is reporting on the full scope of the errors possible and not understating the effect of the larger errors. It must also be noted that the minimum value for each local model is not exactly zero meaning that the iLiDAR is not precisely synchronous with the TLS dataset but that based on the local model used it very closely approximates our TLS in these areas. This was seen as we expand the values to further decimal places and see the residual error in the iLiDAR measurements. However, these small errors were submillimetre which are not measurable in practice and thus the exact value could not be used. Based on data long scan lines only increased the chance of misalignment due to drift. A possible reason for this relation between scan length and misalignment was due to a decreased potential for overlap during the scanning process as longer scan lines make the iLiDAR scan more dependent on maintaining good IMU capability i.e., longer scan lines needed a very good fix on its orientation and position in space than shorter scans, in addition to less available area for overlap.

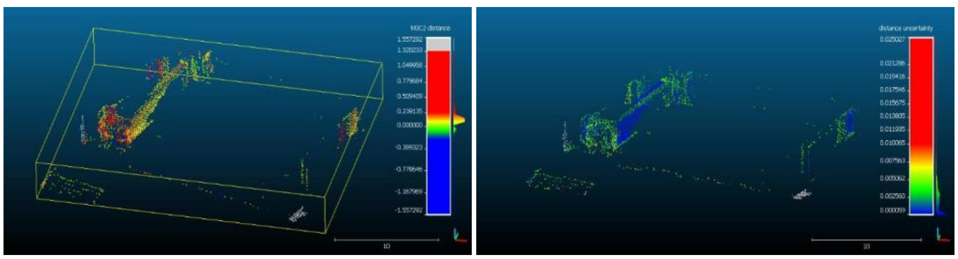

Figure 4 Illustration of where differences or errors lay in the 2m scan (Blue region=low M3C2 distance, low uncertainty ranging through green, yellow and orange, while Red regions =high uncertainty and high M3C2 distances

It must be carefully noted that it is a lack of overlap in conjunction with the limit IMU ability of the iPhone that produces these errors. This is reciprocated in the areas within the 4m scan which had shorter scans lines but much more stable deliverables since a 4m scan will have a larger scope of the object being scanned there will be greater opportunity for overlap. This was therefore the primary reason that the 2m scan failed many to reach higher accuracies in comparison to the 4m scan.

Conclusions and recommendations

The aim of this study was to evaluate the accuracy that the iPhone 12 Pro LiDAR scanner with its GNSS positions with respect to commercial grade point clouds. We see from the above results that the iLiDAR performed well for a fit for purpose tool in the 4m scans, but also largely in the 2m scans. However, it can be noted for highly accurate work that its GNSS capability not only failed to provide adequate absolute accuracy as anticipated, but it did not aid at all in maintaining good iLiDAR measurement capability as seen in mobile laser scanning (MLS). To address the possible methods of providing optimal results from the iLiDAR system, it is with strong recommendation that a proper stabilizer be used for the acquisition of the iLiDAR if greatest accuracy is desired. This would allow the IMU capabilities of the iPhone to work optimally with the SLAM algorithm in addition may also benefit from an external GNSS receiver. The researchers also recommend further research towards more integrated approaches with structure from motion photogrammetry to deliver textured models to users and reinforce the limitations of the iLiDAR system which may provide the near 1cm accuracy claimed by Apple developers.

Acknowledgements, Conflict of interest and Author contributions

[anon]

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MOBILE PHONE BASED LiDAR AS A LOW-COST ALTERNATIVE FOR MULTI-DISCPLINARY DATA COLLECTION

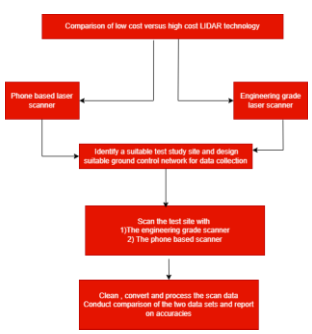
Abstract

Airborne and terrestrial laser scanners~~ing~~ have traditionally been used as specialised toolsets for three-dimensional scene capture in engineering, providing highly accurate measurements with minimal human interaction. However, the commercial grade of these instruments remains expensive and sensitive, requiring costly routine calibrations to ensure their optimum functionality. The recent inclusion of ~~a~~ laser scanning sensors by mobile phone manufacturers such as Apple is now analogous to ~~the integration of~~integrating ~~the~~ ~~global~~ Global ~~navigation~~ Navigation ~~satellite~~ Satellite ~~systems~~ Systems (GNSS) and cameras into phones as seen decades ago. ~~,~~ It is likely that these initial efforts to include the scanning sensor in mobile phones will see rapid improvements in the application and accuracy of the sensor to serve the growing need of scanning data for ~~transdisciplinary~~ transdisciplinary users. However, there is a limited amount of literature that benchmarks emerging and low-cost scanning sensors to existing commercial ones to inform ~~practise~~practice, thus prompting a need for researchers to evaluate and provide scientific evidence that can inform multi-disciplinary scanning ~~practises~~. The researchers, ~~therefore,~~ investigated the extent to which laser scanning ~~tools~~ tools are available within ~~the~~ iPhone 12 Pro compared to the ~~engineering grade~~grade engineering-grade laser scanner. Outcomes from the research showed that iPhone scanners can deliver ~~the~~ required models, despite ~~albeit being~~ being relatively unstable when pitched against traditional LiDAR scanners. It was also noted that there was some absolute positional shift and scan drift in the data. The research recommends that stabilizers such as gimbals or enhanced GNSS receivers, could be in used in practice to achieve improved accuracy from the mobile phone (iPhone) LiDAR.

Keywords: Multidisciplinary, Mobile Technologies, Laser Scanning, accuracy, low-cost, iLiDAR, sustainable solutions

Significance: Low-cost tool for curating models in three dimensions; Fit for approach purpose in multi-disciplinary science

~~**Graphical Abstract**~~



Introduction, Background and Aims

Light ~~detection~~ Detection and ~~ranging~~ Ranging (LIDAR) scanning systems have over the years allowed users to create observations of any man made or environmental structure for application in hundreds of areas such as geology, archaeology, engineering, and spatial data collection. [1] Airborne and terrestrial scanning methods provide of quick and accurate multi-point positional data capture at increased rates and this approach serves multiple users across the technical context of aerial (ALS), mobile (MLS) and terrestrial laser scanning (TLS) applications [1, 2]. Furthermore, terrestrial laser scanning using high grade equipment provides large volumes of point cloud data with high resolution for topographic mapping, meteorology, archaeology, monitoring deformation, building construction and structure analysis in engineering surveys [1]. These numerous applications have led rapid developments in mechanical and data processing capabilities attempting to make the systems more accurate, efficient, and affordable to a larger market [2]. Recent applications have also extended to various other sciences and arts where physical models are of interest including health sciences, architecture, biodiversity, and many others [3]. However, access to scanning services has remained a barrier to broad application due to the high costs associated with commercial scan equipment and its maintenance plans [4]. Since 2007, when the first iPhone was announced, there has been an increase in similar high-end mobile phone interfaces that have claimed to revolutionize many professional disciplines, by offering mass integration of distinguishable technologies with varied purposes, into mobile devices [5]. The rise in popularity of Apple's iPhone is driven by its constant innovations and out of the box utilities [6]. Of recent, Apple's ambition to improve themselves has led to the inclusion of their first (1st) Generation LiDAR (hereinafter referred to as iLiDAR) sensor incorporated into their new iPad Pro and iPhone 12 Pro models and devices beyond up to the more recent iPhone 15[7]. The incorporation of this LiDAR sensor into the phone was intended at improving their Measure Application (app) capabilities by introducing depth sensing, portrait image capability, night mode performance, and Augmented and Virtual video game functionality [86]. It is therefore interesting to benchmark these lower cost sensors to engineering grade. Engineering grade laser scanners are specialized equipment to attain spatial data effectively and accurately, however, at a prohibitive cost of R600,000 to R2,000,000, in addition to routine maintenance to ensure its delivered accuracy[9]. The iPhone 12 Pro and later models costing above R20,000, now provides LiDAR capabilities to the public which claim to provide comparable results, requiring no routine maintenance and offers real time processing. Literature posits that there is insufficient scientific knowledge on the iLiDAR capabilities as there are very few studies that have captured the gains of this recent development from an accuracy perspective [86,9,10]. The problem therefore lies in the limited amount of literature that benchmarks emerging and low-cost LiDAR sensors to existing commercial ones. There is therefore a need for researchers to evaluate and provide evidence that can assist users who may need to use the technology for various applications. This paper aims to test the accuracy of the iPhone's LiDAR sensor and its capabilities with respect to terrestrial laser scanner derived point clouds. The researchers investigated the extent to which an iPhone LiDAR tools available within the iPhone 12 Pro, compares to the engineering grade laser scanner.

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Monitoring how different technologies are being incorporated into existing technologies and how fast they grow in complexity will give an insight into the accuracy available for future data collection options.

Associated theories and literature review on advances in laser scanning technologies.

Several models and frameworks have been developed to explain the user adoption of new technologies with more than one theoretical approach required for a complete understanding of trends in technology. In this paper, adoption theories and models are not significant. However, but due to the practical nature of the findings, which may get dated quickly, with the rapid advances in improved iPhone LiDAR or the sales of other lower-cost LiDAR devices, it is of value to highlight that technology adoption theories explain the changes and growth in development of low-cost devices in the literature. Moving over to the case of the LiDAR sensor in the iPhone mobile gadget, third party applications (apps) capitalized on the opportunity to use this LiDAR system in conjunction with the processing power of its new bionic core, to provide 3D models just as terrestrial LiDAR systems would [3,6]. The three-dimensional (3D) models appealed to multiple disciplines who could use the iLiDAR for reality capture and documentation. Therefore, the additional ability to reconstruct 3D models using the iLiDAR is not accredited to Apple, but several third-party sources who developed these apps to take advantage of the LiDAR system using the app developer's designed algorithm[1]. These sensors' function offers the same scientific concepts as their professional grade counterparts albeit reduced to the most basic components. These apps can produce well textured models through use of a simultaneous localisation and mapping (SLAM) algorithm, which in practice allows for the construction of maps and models through the continuous updating of results using precise determinations of the scanner's location and orientation [11]. This algorithm is used primarily for mobile laser scanning (MLS), as the LiDAR scanner is mounted to some vehicle with the Global Navigation Satellite System (GNSS) and Inertial Measurement ~~nit~~ unit (IMU) systems constantly keeping track of the vehicle during acquisition, where the SLAM algorithm allows for a registration and geo-referencing of all these points [3]. In the research done by ~~(Luetzenburg, Kroon & Bjørk, 2021)~~, [6~~6~~], the accuracy of the iLiDAR systems is quoted to fluctuate between 3cm and 6cm, which demonstrates a high potential for the mapping of small-scale scenes such as residential rooms above. Apart from its use in gaming these capabilities are promising for forensics, real estate, physics, archaeology, and engineering documentation. Despite the rapid growth to increase reach, the addition of these added specialised competences to selected mobile phone would require immense focus on obtaining accurate measurements in real time, and with consideration that professional scanners require maintenance to provide quality data. The measurement principles behind LiDAR scanning are to juxtapose the numerous benefits and applications of the technology, sharing similar base concept of electronic distance measurements. LiDAR is at its core is a range detection method using a laser pulse to illuminate an object and measuring the time taken for this pulse to return to the source allowing the LiDAR scanner to accurately measure the distance between the sensor and the object.[1,2, 11] From the interaction of the laser pulse with an environment a three-dimensional impression of the real world is recreated with a collection of X, Y and Z coordinates for multiple locations. LiDAR sensing

[1] https://www.apple.com/newsroom/2020/03/apple-unveils-new-ipad-pro-with-lidar-scanner-and-trackpad-support-in-ipados/

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under low light condition providing overall accuracies of 0.191 metres (m), 0.242m, 0.345m at 20m, 40m, 60m altitudes [7]. Commercial terrestrial and mobile can achieve an accuracy of less than 20 millimetres (mm) for Time of Flight (TOF) scanners and less than 10mm for phase difference scanner [7]. It should be noted that this is a very general estimate due to the wide range of LiDAR scanners available on the market, as many can provide between 3mm and 6mm accuracies. Mobile laser scanning takes the concept of terrestrial or ground-based laser scanning but by adding a real time kinematic GNSS and inertial measurement unit (IMU) systems for a moving platform. This allows scanning to take place in rapid succession by driving a LiDAR scanner mounted to a vehicle/platform and producing a geo-referenced point cloud through registration.

The iPhone LiDAR (iLIDAR) scanner on the other hand is a combination of model sensors that provides users with the potential to approximate engineering grade mapping capabilities, as it combines a refined GNSS receiver, enhanced gyroscope, and accelerometer sensor as well as what is described as a high precision camera sensors and LiDAR sensor. In the research done by [78] (Tavani et al., 2022), the author described the iPhone 12 Pro LiDAR system as a paradigm shift, improving the geospatial data acquisition process through acquiring three-dimensional (3D) reconstruction models for fieldwork in real time. The study resonates with related work and posits that such a capability in the hands of scientist, such as geologists, would improve research fieldwork opportunities by increasing access to low-cost LiDAR data, and enhancing repeatability and transparency [3,5,6]. It is possible to add location or GNSS capability using the iPhone 12 Pro GNSS receiver, however, due to the low resolution available to these sensors, absolute accuracy will not approach engineering grade standards. However, in a study conducted by [810] (Tamimi, 2022), they concluded that the use of an external RTK GNSS receiver connected to the iPhone 12 via Bluetooth, may provide much higher accuracies by using much more defined positional information. It is, therefore, the purposes of this research to evaluate whether the same is true without the RTK receiver, not to evaluate absolute accuracy but to evaluate if GNSS positions from the built-in receiver aid in any way to the final deliverable. Still regarding [810] (Tamimi, 2022) the iLiDAR data accuracy did not increase too significantly between Generation 1 to Generation 2 LiDAR and camera systems. Overall, relative accuracy is exceptionally low when compared to that of total station data or a comparison to what we have in laser scanners as for most results we may only attain <10 centimeter (cm) of accuracy. However, the iLiDAR point accuracy maintains at satisfyingly at <1cm at points close to the start as advertised as there still exists the same drift as the iPhone 12 which makes it incompatible and insufficient for mapping and even dangerous. To that point, however, we can supplement the iPhone data with correctly surveyed control points we can reduce this error such that one could say it is relatively accurate if we understand the results should be. The iPhone 13, a later model than iPhone 12, does hold its positional accuracy overall and their colorized point's works lines up neatly with the point cloud.

According to the numerous studies conducted for comparing two-point cloud datasets including [7](Santise et al., 2018), [132] (Chauhan et al., 2021), and [13](Ahmad Fuad et al., 2018), a trend for a defined accuracy assessment procedure that mirrors the one initiated by [14](Gillihan, 2021) is is evident. In the work conducted

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by [14] ~~(Gillihan, 2021)~~, the suitability of the iLiDAR sensor for forensic work was interrogated. The researchers used three techniques for LiDAR comparison including a cloud-to-cloud comparison, a rudimentary comparison of tape measurements, and chalk outline clarity test. In similar work conducted by [13]~~(Ahmad Fuad et al., 2018)~~, point cloud comparison using two different registration algorithms. Individual point clouds were aligned together in Cloud Compare and made use of the cloud-to-cloud distance model computations. According to [[13]~~(Ahmad Fuad et al., 2018)~~, three-dimensional (3D) deviation analysis between point cloud is best performed using a cloud-to-cloud computation to provide for a comparison of the entire range of available points instead of a point-to-point or point-to-cloud method. In the research conducted by [13] ~~(Chauhan et al., 2021)~~, two distinct distance models can be used: the Cloud-to-Cloud Comparison, Cloud-to-Cloud (C2C) Distance, and Multi Scale Model-to-Model(M2M) Cloud Comparison, Model-to-Model Cloud (M3C2) Distance. Based on literature [11] the iLiDAR scans conducted using two different scanning method can be compared based on overlap they provide as well as an estimation of the drift seen in the data and how it manages elevation changes. This allowed the researchers to consider how diverse data collectors can conduct their work. The current study adopts C2C and M3C2 approaches in comparing the derived point clouds due to its statistical robustness that makes it reliable and scientifically sound in tests.

Material and Methods

Cape Town is on South Africa's southwestern coast close to the Cape of Good Hope and is the southernmost city on the African continent The study site selected for this investigation was a modern building within Rondebosch, Cape Town, South Africa. The Snape and Menzies buildings[2] in Rondebosch were selected as study sites and~~they~~ presented regular but complex shapes with several stairs and corridors that are ideal for robust testing for the case at hand. It is important to highlight for ethical considerations that the authors have obtained ethical clearance to conduct the work and have no link with Apple. The~~T~~t the device is selected as it is one of the few mainstream mobile technologies at present that have introduced scanning technology, something that directly intersects with the researcher's line of work, it is for this reason that the iPhone LiDAR made a good candidate for further investigation. The researchers reflected on the overall method of data capture to ensure that all necessary data would be collected optimally and in a state that makes it ready to use when preforming the analysis. The primary consideration towards selection of the building venue was also due to the iPhone 12 LiDAR scanner accommodation into the plan and limitations it may face with regards to the uncertainties it may be required to measure. To kick off data collection, the initial field step was to set up control points that would be a network guide for the tests. When establishing the control network, it was important to first plan out provisional scan position to ensure that there will be enough control in the system

2 https://uct.ac.za/contacts-maps/buildings-departments-and-offices

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to minimize the errors and geo-referenced the scans. Two additional ground control points (GCPs) were placed outside of the test site and observed using Virtual Reference Station Real Time Kinematic (VRS RTK) GNSS due to limited nearby control and limited GNSS reliability in built up areas. As highlighted above, to evaluate the integrity of the iPhone 12 LiDAR scanner it was compared to a terrestrial laser scanner point cloud (both a Trimble Laser scanner and Z and F scanner). To make a comparison of the scans and register the two LiDAR point clouds, targets were placed on the walls wherever possible. These targets were black and white markers and were placed about 1.5 meters above the ground. Targets were not placed all around completely, because to whether conditions that day, and instead chose noticeable features like the edges of signs for the remaining segments of the building. The Trimble X7 (TLS)and Z and F scanner allowed for a cloud-to-cloud registration which can be done in the field and therefore the relationship between scans and ground control points (GCPs) were not as vital, as in the methods of the past. Setup positions were chosen based on the desired amount of detail and overlap between scans as well as proximity to the available GCPs. Since the iPhone LiDAR needed to be on the same coordinate system as the laser point cloud for seamless comparison and to keep good positional accuracy for the iPhone during data capture, open source GNSS data was be used. Thereafter cleaning of the data which amounted to removing all unnecessary features from the point cloud was conducted. This was to ensure that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. Once the data was ready, the two datasets from the terrestrial scanner and the phone scanner were further processed and compared to highlight similarities and key differences. An accuracy-based approach to the comparison was adopted using algorithms within Cloud Compare. Cleaning the data amounted to remove all unnecessary features from the point cloud such that only the building feature, paths and steps were accounted for was conducted. This was to ensure that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. Using the field data for the iLiDAR scans, the researchers were able to produce a workable deliverable by following a similar workflow to that of mobile laser scanning due to the similarities in the data acquisition process. However, to add to this the process, the iLiDAR scans will also include a registration step as the scanning process was done per wall to reduce strain on the iPhone processing unite.

Results and Discussions

Using the field data for the iLiDAR scans, the researchers were able to follow a similar workflow to that of processing mobile laser scanning (MLS) due to the similarities it holds with the iLiDAR data acquisition proces~~ss. However, to add to this the process,~~ T~~t~~he iLiDAR scans also required a registration step as the scanning process had to be done per wall to reduce strain on the iPhone processing unit. The~~reafter,~~ cleaning of the~~the~~ collected data involved removing all unnecessary features from the point cloud such that only the building feature, paths and steps were accounted (Figure 1~~Figure 1~~). This ~~was to~~ ensured that the cloud has the same features as the iLiDAR point cloud must enable a correct comparison between these two datasets. During the importing process

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Commented [R25]: Is this not methodology (what you did) - it cant be part of the results the iLIDAR point clouds appeared to struggle to be interoperable with the software of choice, and when loaded the point cloud would either be extremely small or disintegrate into an extensive line of points. A probable reason for this may be due to either the processing done by the A14 bionic chip within that may not be allowing the cloud to communicate to the computer correctly or may also deal with the way the iPhone 12 formed the geo-referenced file. This was as expected and seen with many Apple devices where compatibility with other platforms may not always be smooth as we see in related work by [15,16]. [***].

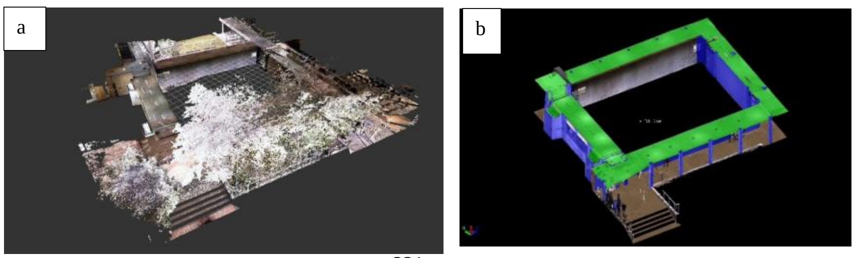

Figure 1: a) Uncleaned Trimble Laser Scanner (TLS) point cloud; b) Cleaned and classified TLS point cloud

After cleaning some further inspection of the data followed. Another challenge identified was that since the iLiDAR could only have minimal overlap areas at the edges for each wall, a least square adjustment matching solution would cause walls to be inverted in the opposite direction. This was because the matching algorithm views the maximum amount of area within the scans overlap region by tying in other similar features to one another. However, this would cause the scan to be mirrored to one another so that the faces of the features are overlapped on top of one another orientated in the same direction. This in practice could be solved with an additional point at the end of the wall to keep the orientation of each scan defined. This meant that the iLiDAR scans now had to be aligned to the Trimble Laser Scanner (TLS) dataset so that the scans were aligned correctly. The iLiDAR cloud was then orientated to the TLS cloud using a Rotate or Align function and it was finely aligned using the Finely Align function to correct for the remaining orientation discrepancies and overlay the two scans together. This effectively registered the two clouds together with the TLS cloud as a reference after 20 iterations and five thousand random point samplings. The aligned scans were merged into one point cloud for both two meter (m) and 4m scans. The 4m scan contained the inside corridor. Since the inside corridor needed enough points to tie the scan into the remaining other scans it was integrated into the 4m scan. Though the scan could not have been done with a 4m scan range, this choice is justifiable as scanning was done using the maximum possible distance away from the object. These merged scans were exported into Trimble Business Centre (TBC) to be classified and cleaned further. The accuracy of the iLiDAR point cloud could now be evaluated further by the researchers, using visual interpretation and cloud to cloud (C2C) distance models as adopted from literature, which compute the distance between two respective points in a point cloud. Regarding the cloud distance methods, the detection and removal of outliers was firstly conducted

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using a python program. The results were summarized to highlight the change in centrality for each local model, providing insight into the skewness, concentration, and distribution of the data. Visual analysis of this data was summarized in descriptive statistics tables which gave an overall mean and 95% confidence interval for each scan. The products of the M3C2 Distance algorithms were also provided with their own corresponding tabulations and heat maps with respect to the C2C Distance method. The M3C2 provided distance comparisons and summaries for its own cloud distance computations and an analysis of the statistical models used for conveying the product's precision.

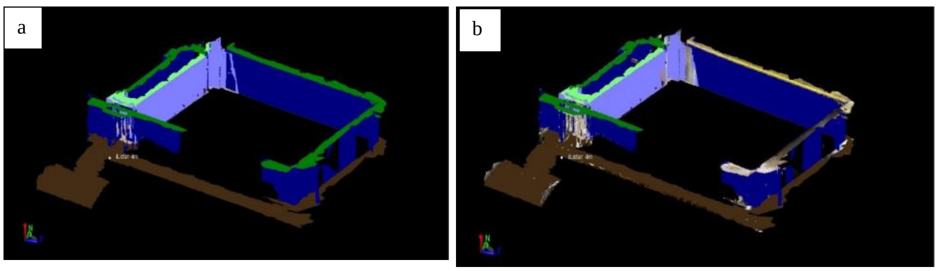

Figure 2 Images of a) TLS and b) iLiDAR point cloud alignment and cloud registration in Cloud Compare for 4m scan.

Table *1*: ~~Table 1 shows descriptive statistics table of each C2C Local Model Distances in 2m scan~~ .

Table 1: Summary Statistics of C2C Distance Local Model (iLidar 2m)

Nearest Neighbour		Least Squares PlanE		2D1/2N Triangulation		Quadric Height Function	
Summary of Results		Summary of ResultS		Summary of ResultS		Summary of Results	
Mean (m)	0.080	Mean (m)	0.060	Mean (m)	0.080	Mean (m)	0.061
Standard Error (m)	0.00004	Standard Error (m)	0.00003	Standard Error (m)	0.00004	Standard Error (m)	0.00003
Mode (m)	0.003	Mode (m)	0.001	Mode (m)	0.003	Mode (m)	0.002
Median (m)	0.060	Median (m)	0.043	Median (m)	0.060	Median (m)	0.041
Standard Deviation (m)	0.070	Standard Deviation (m)	0.055	Standard Deviation (m)	0.070	Standard Deviation (m)	0.057
Sample Variance (m)	0.005	Sample Variance (m)	0.003	Sample Variance (m)	0.005	Sample Variance (m)	0.003
Range (m)	0.314	Range (m)	0.228	Range (m)	0.314	Range (m)	0.233
Maximum (m)	0.314	Maximum (m)	0.228	Maximum (m)	0.314	Maximum (m)	0.233
Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000	Minimum (m)	0.000
Points	3131245	Points	3165355	Points	3129841	Points	3160523
Sum (m)	250782.6	Sum (m)	190980.5	Sum (m)	250440.5	Sum (m)	191504.1
Classes	1770	Classes	1780	Classes	1770	Classes	1778
Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)		Confidence Interval (95%)	

Lower CI (m)	0.079	Lower CI (m)	0.059	Lower CI (m)	0.078	Lower CI (m)	0.059
Upper CI (m)	0.082	Upper CI (m)	0.062	Upper CI (m)	0.082	Upper CI (m)	0.062

The removal of outliers using percentiles caused a change in accuracy of 1.3cm indicating that these are groups of large values, up to 60cm, in small proportions implying that potential outliers were removed. Evaluating the data across all the local models revealed that the relative accuracy of the iLiDAR was between six centimetres (cm) and 8cm, on average. All models showed low variability with a standard deviation (SD) fluctuating between 5.5 and 7), and standard error measures close to zero implying that these averages are good estimators of the true mean. In addition, the 95% confidence interval in each model allowed for a 3mm window for its estimation of the true mean, implying strongly that these means closely approximate this value. The final outputs of each C2C Distance local model used in the iLiDAR comparison for the 2m scan, were also prepared with its scalar field colour ramp as illustrated in Figure 3 , showing the colour corresponding to the distance calculated and a 10m scale bar. The dataset showed the visual distributions of the departures across the object surface revealing the areas demonstrating the most and least variation from the TLS dataset.

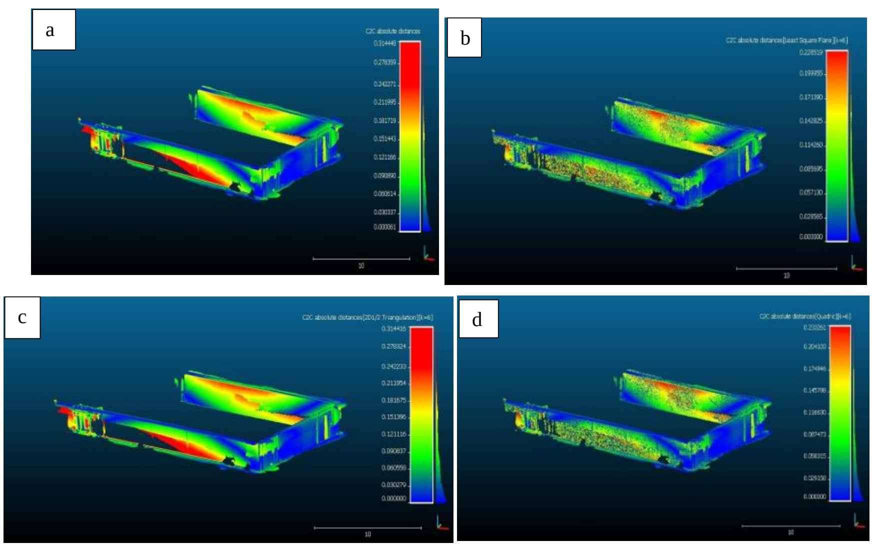

Figure 3 *a) C2C Distance – Nearest Neighbour for 2m scan b) C2C Distance – Least Squares Plane for 2m scan c) C2C Distance – 2D ½ Triangulation for 2m scan d) C2C Distance – Quadratic Height Function for 2m scan with its scalar field ramp, scale bar and orthogonal axes*

Red regions on heatmaps, remained consistent between all local models; however, some models are more lenient with reporting the effect of these areas have on the data. The red areas within the nearest neighbour (NN) and Two-dimensional Triangulation (2DT) models have more missing data in these regions which indicate that these are the locations were most outliers were removed. The converse also remains true with regards to blue areas showing very stable results across all models having very dense point counts and show extraordinarily slight variation across all models such as the west wall. Areas of interest regarding larger error values include the north (front facing wall) entrance and its adjacent wall segments. These areas appear more speckled in the Least Squares Plane (LSP) and Quadratics Height Function (QHF) models with very random error responses ranging from exceptionally large, 22cm, and exceedingly small, close to zero. In the results of the above methodology, the researchers aimed to evaluate whether the factors of our initial view on the comparison of accuracies of iLiDAR with commercial scanners would coincide with what we observed in the field. A cloud-to-cloud distance assessment provided for an approximation of the iLiDAR accuracy using descriptive statistics providing different averages for the distance discrepancies giving a general idea of what the system can give a 95% confidence. In addition, the use of the root mean square (RMS) and Chi-squared results give a final estimate of the average error observed and showed how well the data can be modelled. Results provided a comparison of distances across the 2m and 4m datasets to evaluate if the scanning method yields contrary results to the view or reasserts them. Upon visual inspection of the cloud datasets, all point clouds showed significant departures and large segments of discontinuity in the iLiDAR clouds. However, as a general summary, the iLiDAR seemed to approximate the TLS dataset well, specifically within the 4m scan. of the data in the negative direction and represented points behind the wall which could not have been possible. This gave more credence that the lenient local models which produce more noise are utilizing erroneous inclusions into its computations. For each local model, the data conveyed that the best estimate of the mean using that algorithm is only 1mm different from the true mean. This did not imply that the population mean for the iLiDAR scan was 1mm away from these estimates, but it reported on the confidence we have in mean computed for that specific algorithm.

Since the 4m scan outperformed the 2m in this manner, it implied that the 4m provides the more authentic estimation of the accuracy available to the iLiDAR. This was further seen by considering the descriptive statistics tables to their Weibull distribution, where beta values, *b*, decreased from about 0.8 – 0.6, to 0.33 – 0.26 which meant that there was more conformity in terms of a lack of reliability to reach the larger error values in the 4m scan than in the 2m. Within the 2m scan, it was noted that due to this the noisier local models had to come into further evaluation because it was known that it is wrong to assume lower reliability to reach larger values in these areas as we know that the iLiDAR skewed because of drift. However, in the 4m scan there was more agreement between the models, and though the reliability on achieving larger values has decreased, there was more trust in this assessment since we observe less drift errors. In addition, because of the scale, and shift parameters it was seen that the reliability was more defined over its error classes which implies that the Weibull distribution is reporting on the full scope of the errors possible and not understating the effect of the larger errors. It must also be noted that the minimum value for each local model is not exactly zero meaning that the iLiDAR is not precisely synchronous with the TLS dataset but that based on the local model used it very closely approximates our TLS in these areas. This was seen as we expand the values to further decimal places and see the residual error in the iLiDAR measurements. However, these small errors were submillimetre which are not measurable in practice and thus the exact value could not be used. Based on data long scan lines only increased the chance of misalignment due to drift. A possible reason for this relation between scan length and misalignment was due to a decreased potential for overlap during the scanning process as longer scan lines make the iLiDAR scan more dependent on maintaining good IMU capability i.e., longer scan lines needed a very good fix on its orientation and position in space than shorter scans, in addition to less available area for overlap.

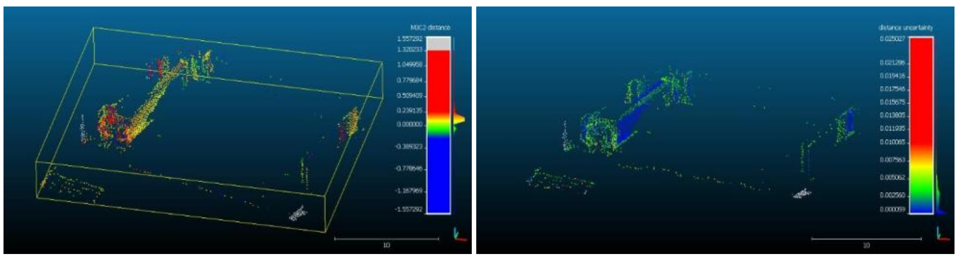

Figure 4 Illustration of where differences or errors lay in the 2m scan (Blue region=low M3C2 distance, low uncertainty ranging through green, yellow and orange, while Red regions =high uncertainty and high M3C2 distances

It must be carefully noted that it is a lack of overlap in conjunction with the limit IMU ability of the iPhone that produces these errors. This is reciprocated in the areas within the 4m scan which had shorter scans lines but much more stable deliverables since a 4m scan will have a larger scope of the object being scanned there will be greater opportunity for overlap. This was therefore the primary reason that the 2m scan failed many to reach higher accuracies in comparison to the 4m scan.

Conclusions and recommendations

The aim of this study was to evaluate the accuracy that the iPhone 12 Pro LiDAR scanner with its GNSS positions with respect to commercial grade point clouds. We see from the above results that the iLiDAR performed well for a fit for purpose tool in the 4m scans, but also largely in the 2m scans. However, it can be noted for highly accurate work that its GNSS capability not only failed to provide adequate absolute accuracy as anticipated, but it did not aid at all in maintaining good iLiDAR measurement capability as seen in mobile laser scanning (MLS). To address the possible methods of providing optimal results from the iLiDAR system, it is with strong recommendation that a proper stabilizer be used for the acquisition of the iLiDAR if greatest accuracy is desired. This would allow the IMU capabilities of the iPhone to work optimally with the SLAM algorithm in addition may also benefit from an external GNSS receiver. The researchers also recommend further research towards more integrated approaches with structure from motion photogrammetry to deliver textured models to users and reinforce the limitations of the iLiDAR system which may provide the near 1cm accuracy claimed by Apple developers.

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