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Revolutionizing Depth Sensing: A Review Study of Apple LiDAR Sensor for as-built Scanning Applications

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ABSTRACT

Incorporating the LiDAR sensor in the most recent Apple devices represents a substantial development in 3D mapping technology. Meanwhile, Apple's Lidar is still a new sensor. Therefore, this article reviews the potential uses of the Apple Lidar sensor in various fields, including engineering and construction, focusing on indoor and outdoor as-built 3D mapping and cultural heritage conservation. The affordable cost and shorter observation times compared to traditional surveying and other remote sensing techniques make the Apple Lidar an attractive choice among scholars and professionals. This article highlights the need for continued research on the Apple LiDAR sensor technology while discussing its specifications and limitations. A comprehensive review found that the Apple LiDAR sensor has shown promise in capturing 3D point clouds of small to medium-sized objects with exceptional detail. This technology offers a cost-effective and accessible option to scan areas faster and analyze data more quickly and automatically for 3D mapping and modelling in indoor and outdoor environments, particularly in areas with restricted access when using other traditional techniques. It also opens the door for more sophisticated applications in future studies, including cultural heritage conservation, archaeological investigations and feature detection, building health monitoring and many more.

Keywords: Apple Lidar, Mobile laser scanner, DTOF, TOF, Augmented reality.

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تطورات ثورية في تقنيات استشعار العمق :دراسة مراجعة لمتحسس Apple Lidar وتطبيقاته الحالية

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الخلاصة

يعد ظهور متحسس LiDAR في أحدث أجهزة Apple المحمولة تطورا كبيرا في تقنيات المسح الليزري المحمول وانتاج الخرائط الثلاثية الأبعاد. في الوقت الحالي لا يزال Apple Lidar متحسس جديد لذلك يستعرض هذا المقال الاستخدامات الممكنة والحالية لمستشعر Apple LiDAR في مجموعة متنوعة من المجالات، وتحديدا لأغراض التوثيق الثلاثي الابعاد للبيئات الداخلية والخارجية و بالإضافة إلى استخدامه في الحفاظ على التراث الثقافي. التكلفة المنخفضة والوقت الاقصر في عمليات المسح وجمع البيانات ومعالجتها لهذا المستحسس مقارنة بالمسح التقليدي وتقنيات الاستشعار عن بعد الأخرى تجعل Apple Lidar خيارا شائعا جذابا بين الباحثين والمهنيين. يسلط هذا المقال الضوء على الحاجة إلى الدراسة والبحث المستمر عن تقنية Apple LIDAR لمناقشة واكتشاف مواصفات هذا المستشعر ومحدداته الحالية. من خلال مراجعة شاملة، وجد أن مستشعر Apple LiDAR واعدا في عملية المسح الثلاثية الأبعاد للأهداف الصغيرة والمتوسطة الحجم وبتفاصيل استثنائية. توفر هذه التقنية خيارا فعالا من حيث التكلفة ويمكن استخدامه لمسح المناطق بشكل أسرع وتحليل البيانات بسرعة أكبر وتلقائية لرسم الخرائط والنمذجة ثلاثية الأبعاد في كل من البيئات الداخلية والخارجية، لا سيما في المناطق التي من الصعب الوصول اليها بطرق المسح التقليدية الاخرى. يمكن لهذا المستشعر فتح الباب لتطبيقات أخرى في مجال حفظ التراث الثقافي واكتشافات المواقع الاثرية ومراقبة السلامة البنيوية للبنايات، والتي يمكن أن تكون أكثر تطورا في المستقبل القريب.

الكلمات المفتاحية: Apple Lidar ، الماسح الضوئي بالليزر المحمول ، DTOF، TOF ، الواقع المعزز

1. INTRODUCTION

LiDAR, which stands for Light Detection and Ranging or as widely known as laser scanning (LS), is a surveying technology that measures the range of a target by scanning the object with pulsed laser light and recording the returned pulses with the sensor receiver **(Lopac et al., 2022; Yang et al., 2022; Hakanen et al., 2023)**. LiDAR data is a recorded 3D representation of the features that have been scanned **(Mohammed et al., 2015).** This type of sensor, known as a mobile laser scanner (MLS), includes a stationary laser scanner mounted on a movable platform in addition to inertial measurement units (IMU) and Global navigation satellite system (GNSS) receivers **(Guan et al., 2016; Ibrahim, 2018).** MLS come in various forms, including handheld, backpack, Unmanned Aircraft Vehicle (UAV)-based and wheel-based systems **(Zhu and Hyyppa, 2014; Hyyppä et al., 2020).** One of the MLS types is the handheld scanner, which gives the user the flexibility to adopt different insights because it's not required to be static during data capture or to maintain sufficient overlap among scans and increase coverage of the scene when observing a site **(Zlot et al., 2014; Dewez et al., 2017)**.

One of the approaches used to measure range with these laser scanning sensors is pulsed-based or time of flight (TOF). TOF has emerged as a critical technology for measuring depth in various Lidar applications used in the market and manufacturing **(Padmanabhan et al., 2019)**. Precision timing computation is employed with all TOF laser scanners, this kind of scanner uses a highly precise clock to calculate the difference in time between the transmitted signal and the reflection of the laser pulse **(Stal et al., 2021)**.

Recently, in 2020, a new handheld MLS was released by Apple Inc. as a built-in mobile sensor in the iPhone 12, 13 Pro, and iPad Pro system devices. According to some literature, Apple Lidar is considered a direct TOF (DTOF) sensor that emits light from a grid of vertical-cavity surface-emitting lasers (VCSELs) and detects scattered light using a grid of single-photon avalanche diodes **(Tontini et al., 2020; Spreafico et al., 2021)**, which is a kind of time-of-flight (TOF) sensor produced as a result of improvements in semiconductor minimization, which led to lighter and smaller-sized sensors, making TOF sensors now embedded in mobile phones **(Padmanabhan et al., 2019)**.

The LiDAR sensor represents a significant advancement in mobile device technology. It's a portable scanner that's more affordable and versatile than TLS when scanning at close ranges, making it a viable option. The iPhone Lidar sensor is a novel technology transforming how digital devices interact with their environment. With the integration of lidar sensor technology into the iOS platform, scholars have started employing it in various applications. Therefore, this study attempts to review the novel handheld Apple lidar for its as-built applications in various fields and represent the sensor's specifications and limitations based on existing literature. The physical background of the Lidar technology is also presented, including TOF and DTOF principles.

2. LASER RANGING TECHNIQUES

3D Laser Scanning is classified into three types according to sensor type and computational bases: TOF, phase shift (PS), also called continuous wave (CW), and laser triangulation **(Shan and Toth, 2018)**. These laser-scanning techniques are often employed separately but can also be combined to produce a more flexible scanning system **(Ebrahim, 2015)**.

TOF entails accurately measuring the travelling time of a very short, powerful laser pulse that travels from the laser rangefinder to the object being observed and returns to the instrument after reflecting from the object **(Shan and Toth, 2018)**. This method uses range estimation to calculate the time delay between transmitting the laser pulse from the sensor to the target and returning to the sensor **(San José Alonso et al., 2011; Abed, 2017; Tan et al., 2018).** However, instead of a pulse in CW, the laser method emits a continuous wave of laser radiation. The range value in this instance is calculated by comparing the transmitted and the received signal and measuring the phase difference between them **(Yoon et al., 2011; Béchadergue et al., 2016; Shan and Toth, 2018)**

TOF scanners typically do not perform in the same way as CW scanners. The TOF approach has a more extended range but is a little slower and has a bit less accuracy than the CW method, which has a medium range, high precision, and is usually faster than TOF **(Suchocki, 2020; Suchocki et al., 2020).** The accuracy difference between the two methods could range from a few millimeters to a fraction of a millimeter, depending on the specific implementation and conditions. The measured range of the scanners that use the TOF (200-300m) is greater than the measured range of scanners that use the CW technique (70-80m) **(Ebrahim, 2015).** On the other hand, the laser triangulation sensor (third type) comprises two components: a laser light source and a detector. The laser beam is directed onto the target, and a detector records the reflected signal by focusing the reflected beam through optical triangulation (camera) onto the detector **(Suh, 2019)**, as shown in **Fig. 1**

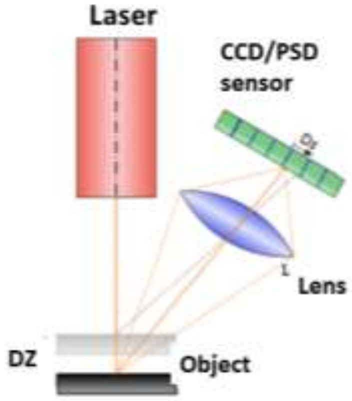

Figure 1. Laser triangulation components **(Ebrahim, 2015).**

If the distance between the laser source and the camera (the baseline D) is known, as well as the angle between the baseline and the laser beam (α) and (β) is the camera field of view, so the 3D position of the laser beam over the target can be determined using trigonometry **(Peiravi and Taabbodi, 2010)**; see **Fig. 2**.

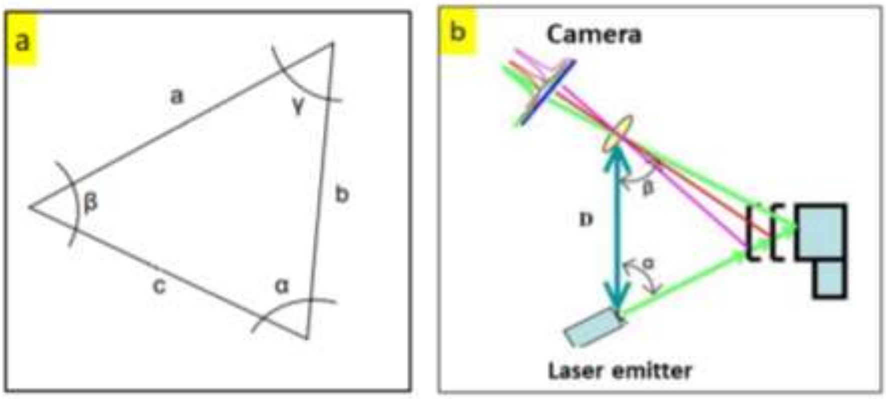

Figure 2. a) Triangulation principal b) Triangulation Laser Scanning Principle **(Lerma et al., 2008)**.

Many measurements based on trigonometry, and employed in Ancient Greece for basic geometrical measurements, can still be used in current laser-based 3D sensors. The same approach is used to observe the environment via a triangulation laser scanner **(Lerma et al., 2008).** Therefore, the triangulation principles can be expressed as follows:

$$\frac{a}{\sin(\alpha)} = \frac{b}{sin(\beta)} = \frac{c}{sin(\gamma)} \tag{1}$$

$$a^2 = b^2 + c^2 - 2.b.c.cos(\alpha) \tag{2}$$

$$C = a.cos(\beta) + b.cos(\alpha) \tag{3}$$

where (a, b and c) are the side lengths and (α, β and γ) are the angles.

Triangulation range finders have a limited range of a few meters, but their accuracy is relatively high. They have an accuracy of a few tens of micrometers **(Ebrahim, 2015)**. The triangulation system is more suitable for measuring small objects and shorter distances. In contrast, the time-of-flight (TOF) system is better equipped to measure larger objects and areas **(Shanoer and Abed, 2018)**.

Ranging techniques based on time delay (TOF sensors) are classified into two types: direct (DTOF) and indirect (ITOF) **(Padmanabhan et al., 2019)**. This article will mainly focus on TOF and DTOF sensors. **Fig. 3** summarises the classification of laser sensors based on available measurement techniques.

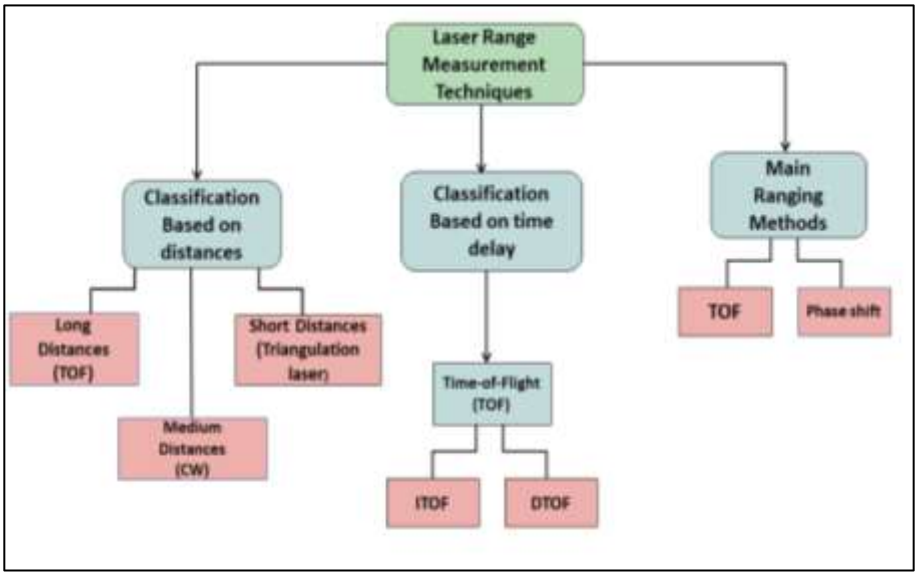

Figure 3. The laser scanning measuring techniques and classification.

3. TOF LASERS-CATEGORIZATION AND PRINCIPLE

Most long-range Lidar systems determine distance via TOF measurements **(Beraldin et al., 2010)**. The TOF Lidar works on the principle that the laser emitter first emits pulse laser light in a specific direction. If the laser light meets an object, it will scatter or diffuse according to the material of the object's surface., see **Fig. 4 (Yang et al., 2022)**.

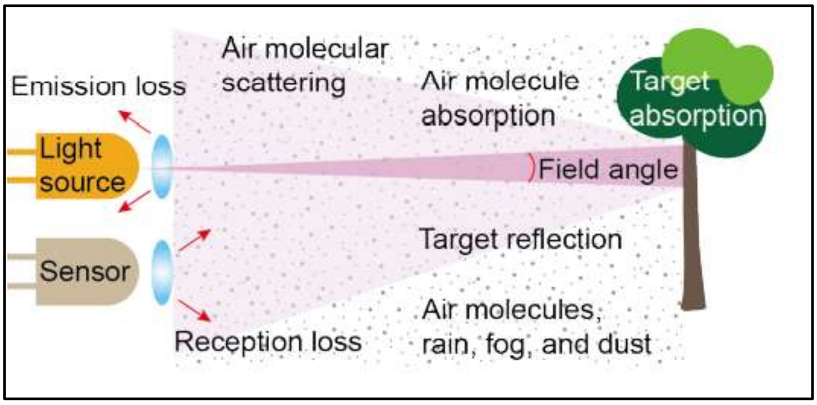

Figure 4. Laser returned signal challenges **(Yang et al., 2022)**.

After receiving the reflected signal, the distance between the sensor and the object is determined by estimating the time it requires for the laser beam to transit from the transmitter sensor to the target and back, see **Fig. 5 (Yang et al., 2022)**.

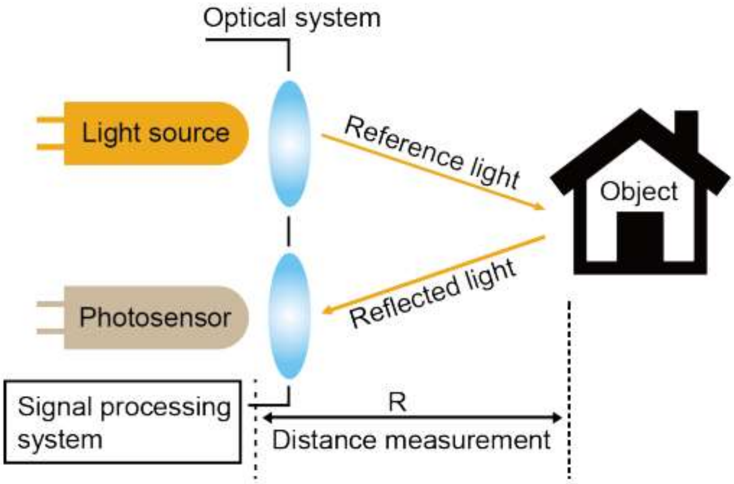

Figure 5. The working concept of ToF LiDAR **(Yang et al., 2022)**.

The measurement formula is as follows **(Jaboyedoff and Derron, 2020)**:

$$R = \frac{c\,\Delta t}{2n} \tag{4}$$

The speed of light is denoted by "c". The index of refraction of air, which serves as the medium for light propagation, is equal to one and is represented by "n". Additionally, Δt represents the duration between the transmission and reception of laser pulses. **(Jaboyedoff and Derron, 2020)**.

However, the reception of a laser beam is not as simple as its emission, see **Fig. 4 (Yang et al., 2022)**. The received laser signal is described by the backscatter coefficient, which can be formulated as follows **(Rasshofer et al., 2011)**:

$$P_{R=} C \; \frac{\beta}{R^2} \; exp\,(-2 \int_{r=0}^{R} \alpha(r)dr) \tag{5}$$

where P_R is the received laser power return at a distance R, C is the light speed constant, α is the absorption coefficient of the LiDAR signal, and β is the reflectance of the object surface. Furthermore, when a wide field of view (FOV) and centimeter-level resolution are required, TOF techniques are the best options **(Villa et al., 2021)**.

TOF sensors are categorized into direct (DTOF) and indirect (ITOF) **Fig. 6**. DTOF is either directly determined by the measurement of the travelling time of a transmitted laser pulse reaching an object and then backscattered from that object or indirectly determined by measuring the phase shift between the transmitted and returned signal **(Park, 2020; Villa et al., 2021)**.

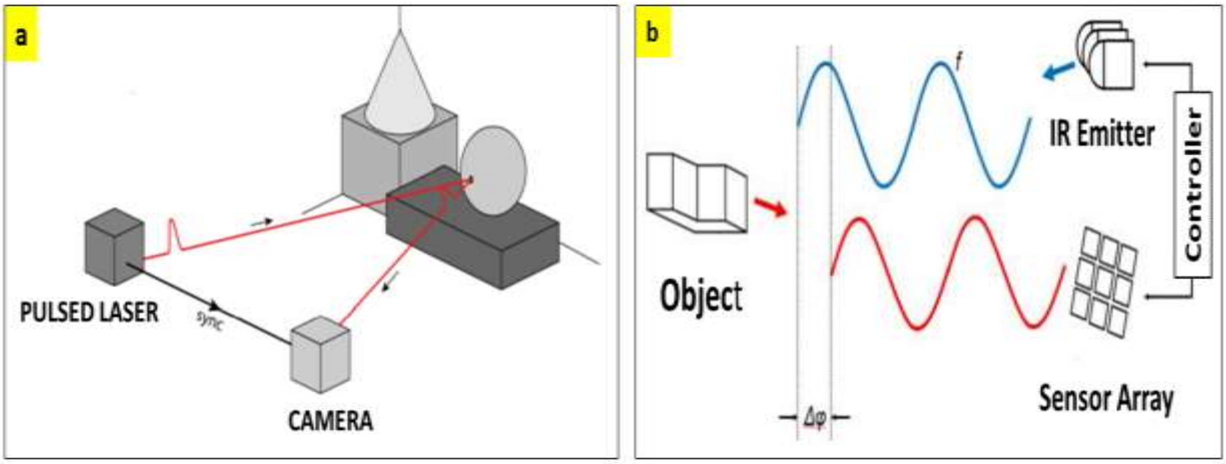

Figure 6. TOF sensors categorization: a) direct time of flight (DTOF) **(Villa et al., 2021)**, b) Indirect time of flight (ITOF) **(Park, 2020)**.

Eq. (6) expresses the fundamental process for transforming time measurements obtained by both techniques into a distance **(Buchner et al., 2020)**:

$$tTOF = \frac{2d}{c0} \tag{6}$$

where the distance is represented by "d", and the speed of light by "C0".

Depth sensing in DTOF is accomplished by sending a regular light source (usually a pulsed laser light) to an object and determining the return of rebounded light with high-performing photodetectors **(Padmanabhan et al., 2019)**. On the other hand, IToF measures a periodic waveform's phase delay. The sensor array reads the phase difference between the modulated emitted and the reflected light signals **(Park, 2020)**. ITOF is illustrated in **(Fig. 6 b)** where the IR transmitter sends modulated light to the object, and the sensor detects the backscattered phase-shifted light.

The transmitted signal in the amplitude-modulated (AM) ITOF is a continuous-wave, time-modulated signal and often a sinusoidal waveform **(Behroozpour et al., 2017; Padmanabhan, 2021).** Therefore, the phase difference between the emitted and received light signals is utilized to calculate the distance the light travels from the sensor to the target and back **(Padmanabhan, 2021)**. As a result, the distance, D_{mod}, can be formulated as follows:

$$D_{mod} = \frac{c\Delta\Phi}{4\,\pi\,fmod} \tag{7}$$

where f_{mod} represents modulated frequency, and c refers to the speed of light.

ITOF is currently restricted to short distances of less than 10 m **(Yamada et al., 2018; Padmanabhan et al., 2019)**. Another limitation of ITOF sensors is their poor capability to discriminate between two close objects (multi-path interference) **(Remondino and Stoppa, 2013; Padmanabhan et al., 2019)**. On the other hand, DTOF sensors can transcend these restrictions with sensing ranges up to 100 meters **(BenMoussa et al., 2016)**, which are mainly determined by the available optical sensor and their inherent capacity to quickly distinguish between multiple echoes **(Padmanabhan et al., 2019)**.

4. TOF MOBILE LASER SCANNER (MLS)

The term "Mobile Mapping System" (MMS) refers to a mobile vehicle, either aerial or terrestrial, that incorporates measuring devices and sensors for gathering georeferenced metric data **(Di Filippo et al., 2018; Di Stefano et al., 2021b)**. A key factor in the growth of MMS has been the downsizing and cost-cutting of mechanical parts, which have made systems more adaptable, portable, and affordable **(Nocerino et al., 2017)**. MMS is, therefore, the integration of the following three hardware parts: optical sensors, navigation/positioning sensors, and a controller **(Di Stefano et al., 2021a)**. When integrated with Light Detection and Ranging (LiDAR), this technique is called MLS, which is typically classified based on the mobile platform utilized.

The MLS measurement is based on LiDAR technology. It stands on a movable platform, in which the accurate orientation and location of the sensor are obtained using a navigation system similar to ALS. Thus, the reflected objects' position can be calculated from pulse transit time or phase information **(Shan and Toth, 2018)**.

Although there are many different types of mobile LiDAR systems, the majority of MLS systems have five fundamental components: a mobile platform, GNSS antenna, Inertial Measurement Unit (IMU), Distance Measurement Indicator (DMI), laser scanner, camera, and control system that incorporates and synchronize all sensor functions and stores all data, i.e., **Fig. 7 (Guan et al., 2016; Wajs et al., 2021).** Standard MLS devices come with various sensors for both the GNSS and IMU. These two elements can verify that the three-dimensional laser scanning data is correctly georeferenced **(Kukko et al., 2012).** The vehicle's trajectory and attitude are provided by the (GNSS) and (IMU), which are used to create the georeferenced 3D point clouds **(Wang et al., 2020; Pöppl et al., 2023).** Since the (GNSS) and (IMU) are two navigation sensors that primarily provide accurate location and orientation measurements of a moving vehicle, DMI, on the other hand, offers supplemental positioning information during a GNSS signal outage **(Guan et al., 2016; Grešla and Jašek, 2023).** The MLS can include more mapping devices, such as thermal imagers and spectrometers **(Shan and Toth, 2018)**.

Figure 7. The components of the MLS system **(Lohani and Yadav, 2018)**.

Furthermore, a wheel-mounted DMI constraint error drifts, particularly during vehicle stops in locations with unstable GNSS service; DMI, which is mounted on one of the vehicle's wheels **see Fig. 8,** measures wheel rotations and directly estimates the distance travelled **(Guan et al., 2016)**.

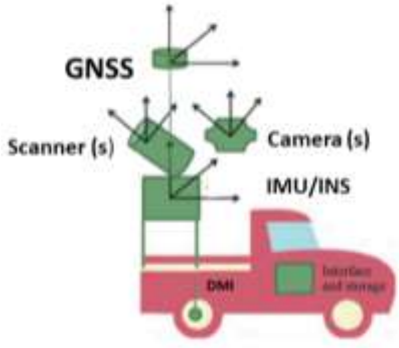

Figure 8. DMI on the vehicle's wheels in the MLS system **(Olsen, 2013)**.

However, GNSS signals are susceptible to external disturbances and can fail when the platform is in a challenging environment like a high building, a mountainous terrain, or an indoor area **(Wang et al., 2020).** As a result, positioning accuracy will decrease as well. Therefore, new techniques, such as the SLAM-based laser scanner, were developed to overcome the abovementioned issue. Concurrent Mapping and Localization (CML), another name for SLAM, is the technique of simultaneously determining the vehicle's location and creating a map of the surrounding area using sensor data **(Azim, 2013; Shi and Peng, 2022).**

MLS systems also provide greater functionality, acquisition, and processing time, delivering high-quality and accurate data. However, object complexities and associated factors, such as environmental location or accessibility restrictions, may make driving in vehicles challenging or restrict access to sites with high scene geometrical complexity, such as archaeological sites **(Rodríguez-Gonzálvez et al., 2017).** The data quality obtained by the MLS system depends on the devices employed. Still, it typically achieves centimeter-level accuracy and resolution in proportion to the speed at which the data is acquired and the distance at which objects are observed **(Gollob et al., 2020)**.

There are two mobile laser scanning platforms: aerial (like an Aerial Laser scanner (ALS)) and terrestrial. There are various types of mobile terrestrial platforms. A sort of terrestrial mobile platform known as a "human-based" platform It refers to user-held platforms that are commonly known as Personal/Portable) Laser Scanning (PLS) or Wearable Laser Scanning (WLS), which the user wears like the backpack laser scanner **(Di Stefano et al., 2021a)**. PLS has the potential to overcome the limitations of other laser scanning (LS) systems, such as the challenge of transferring TLS from one location to another and the fact that vehicle-based MLS only works in places where the terrain conditions are conducive to vehicle movement **(Shan and Toth, 2018)**.

4.1 DTOF Sensing System

DTOF sensors are used in various applications, such as electronic devices for sensing and creating depth maps, to measure range by pulsing a laser and timing the photon return **(Koerner, 2021)**. A pulsed laser emitter, a SPAD receiver array, and one or more time-to-digital converters (TDCs) that process the photon flight time and memory to generate a histogram of the journey times comprise the DToF sensor signal path **(Koerner, 2021)**.

A DTOF sensor consists of a pulsed lighting source, a LED, a photodiode, or a VCSEL (vertical-cavity-surface-emitting laser) grid. This source illuminates the target, and the reflected signals from the target are detected by a suitable photodetector, often an avalanche photodiode (APD) or a single-photon avalanche diode (SPAD) **(Royo and Ballesta, 2019; Li et al., 2020; Padmanabhan, 2021). Fig. 9** illustrates the flow chart of a DTOF system.

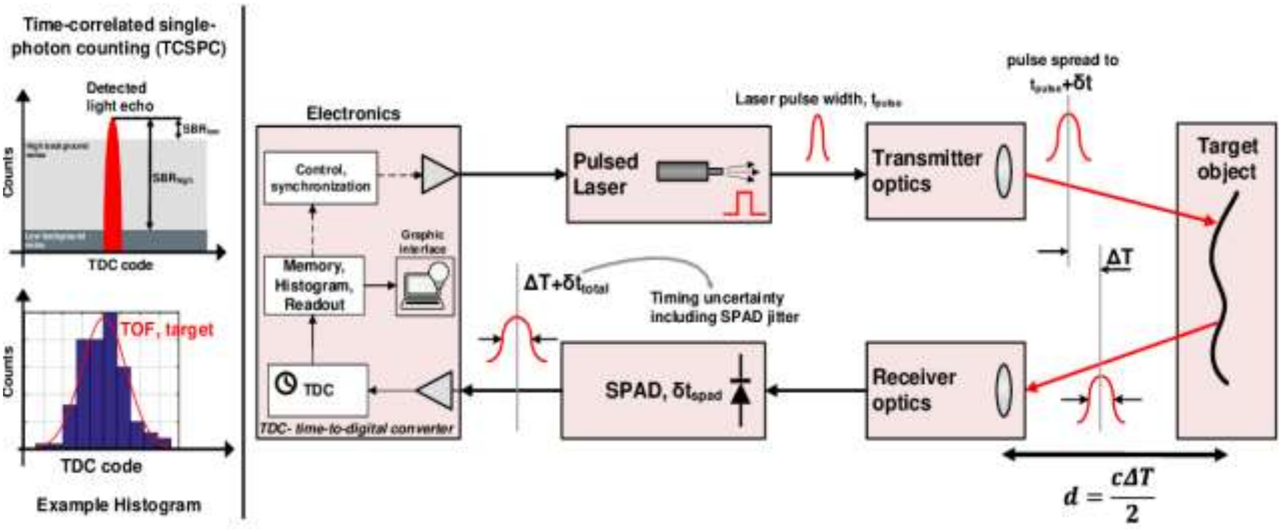

Figure 9. The DTOF sensing system chart **(Padmanabhan, 2021)**.

SPAD arrays incorporated with DTOF sensors have shown good range and 3D imaging abilities, providing an exciting option for PLS systems **(Padmanabhan et al., 2019)**. DToF is mainly based on estimating the round-trip travel time of an emitted pulse to create enough power for illumination **(Dummer et al., 2021)**. A VCSEL or edge-emitting laser array is employed, and a diffractive optical element (DOE) or micro lens array (MLA) shapes the light to illuminate the required field of view. As well as an avalanche photodiode (APD) or SPAD array capable of detecting light with a timer initiated by a light pulse and used to determine the round-trip travelling time **(Dummer et al., 2021)**. Therefore, a time-stamping electrical system determines the photon's arrival time. For this aim, time-to-digital converters (TDCs) are commonly utilized in DTOF sensors **(Padmanabhan, 2021)**.

The most common approach for conducting a DTOF measurement is Time-correlated-single-photon counting (TCSP), which accumulates observed signals over a number of laser pulses emitted at the target **(Padmanabhan et al., 2019)**. The reconstructed signal is a series of pulses represented as a histogram related to each photon's arrival time reaching the SPAD **(Niclass et al., 2014; Padmanabha et al., 2019)**. The estimated target distance, d, from the sensor is then calculated using the measured timing information (ΔT in **Fig.9**) and the speed of light, c.

4.2 Apple Lidar Sensor (Low-Cost PLS Sensor)

Developments in processing techniques and computer capacity have produced small 3D sensors that can provide nearly real-time data at a low cost compared to conventional measurement techniques **(Murtiyoso et al., 2021)**. In 2020, Apple began incorporating lidar sensors into its smartphone and tablet devices see **Fig. 10**. For example, the lidar sensor has been included in the iPhone 12 Pro and Pro Max, the iPhone 13 Pro and Pro Max, the iPhone

14 Pro and iPhone 14 Pro Max, and the iPad Pro. Compared to costly solutions based on TLS or MLS systems, it is considered an affordable and low-cost LS device. Regarding price, the iPad Pro's fourth-generation (4G) Long-Term Evolution (LTE) version is about 1809 USD, and the cost of the iPhone 12 Pro, as of January 2022, is approximately 1170 USD. However, the prices according to January 2023 are around 1079 and 678 USD for the iPad and iPhone 12 Pro, respectively.

Figure 10. Lidar sensor in Apple smartphones and tablets.

Apple has announced the installation of the LiDAR sensor in the iPhone Pro and iPad Pro devices to improve the camera's quality, like camera focusing and allowing 3D capturing **(Franklin, 2020)**. In terms of 3D capturing, LiDAR enables acquiring measurements, creating point clouds or meshes, and integrating data in Virtual Reality (VR) or Augmented Reality (AR) worlds through a variety of apps **(Franklin, 2020; Díaz-Vilariño et al., 2022)**. True depth is primarily utilized in iOS (the operating system for Apple's phones and tablets) for 3D face recognition and identification. In contrast, LiDAR speeds up plane tracking to enable new capabilities for AR applications **(Vogt et al., 2021)**.

Various applications have been built and developed to utilize the potential provided by the sensors integrated into these handheld devices to measure 3D data and produce colored 3D models, not only depending on the lidar sensors built in these devices but also employing data derived from other integrated sensors **(Teppati Losè et al., 2022)**. Examples of LiDAR-based applications are: (Polycam, Scaniverse, 3D scanner app, Everypoint and Sitescape). The LiDAR Scanner performs at the photon level at nanosecond speeds, estimates distances to surrounding objects up to 5 meters away, and can be used indoors and outdoors **(Franklin, 2020)**. However, Apple hasn't provided any technical information for the LiDAR sensor, such as precision and accuracy. Some researchers claim that the recently launched Apple lidar (PLS) sensor in the iPhone Pro and iPad Pro series is a scanner lidar based on the DTOF approach **(Bookhahn et al., 2021)**.

5. APPLICATION REVIEW OF APPLE LIDAR SENSOR

Although Apple lidar is still a new sensor, many researchers have been interested in the Apple lidar sensor and have employed it in a range of applications because of its novelty and lower cost when compared to other remote sensing techniques.

(Gollob et al., 2021) discussed the use of Apple iPad Pro LiDAR for applications related to forest inventories. Three different apps were examined using a suitable acquisition strategy, and the results were compared to other range-based techniques and standard measuring procedures for tree diameter measurement. This versatile and low-cost sensor was suitable for forest inventory, achieving satisfactory accuracy and precision compared to conventional approaches.

Later, **(Vogt et al., 2021)** used Apple Lidar for industrial applications. They aimed to compare the performance of the iPad Pro's integrated LiDAR and True Depth capabilities with commercial handheld 3D scanners (the industrial Artec Space Spider Handheld scanner). The results from the commercial 3D scanner were more accurate. However, this mainly depends on the application, as the accuracy of the smart device could be acceptable. The scanning capability of the iPad Pro was found to be ineffective for scanning small objects such as Lego blocks. As a result, no data were obtained to determine the accuracy of the data. The authors concluded that, at this point, the capability presented by these devices may not be adequate in most industrial applications; however, they may meet particular applications with lower accuracy requirements.

On the other hand, **(Luetzenburg et al., 2021)** evaluated the applicability of the iPhone 12 pro and iPad pro-Lidar scanner for geoscience applications by technological capacity in terms of accuracy and precision of the sensor. They deliver accessibility on-site at a coastal cliff using the "3D scanner app"; then the output was compared with SfM MVS photogrammetry on the mobile phone using the "Every point app”. It was shown that the LiDAR sensors in the iPad and the iPhone are identical because there were no differences between the iPad and iPhone results regarding point density, the total number of emitted points, etc.

Later, Apple Lidar was used to measure snow depth by **(King et al., 2022),** who tested the device's performance in cold weather. They evaluate the ability of the iPhone 12 Pro Lidar to monitor changes in snow depth over time in a narrow area. Compared to snow ruler readings, they concluded that iPhone Lidar could accurately record daily variations in snow depth.

The iPhone 12 Pro's embedded Lidar sensor has also been tested for measuring the human body, demonstrating the technology's potential in numerous applications **(Mikalai et al., 2022).** Some of these are listed below:

5.1 The Deployment of Apple Lidar in Indoor and Outdoor 3D Mapping

The necessity for accurate and realistic 3D models of indoor and outdoor environments has expanded dramatically due to their wide range of applications, including construction, route planning, preservation and restoration of cultural and historical heritage, and the creation of Building Information Modeling (BIM) **(Erzaij and Obaid, 2017; Jakovljević and Taboada, 2022; Alkarawi and Jaber, 2023).** The researcher intended to investigate the capability of the novel Lidar sensor for indoor and outdoor 3D mapping.

Later, in 2022, **(Díaz-Vilariño et al., 2022)** used the iPad Pro to test the capabilities of Apple Lidar for indoor and outdoor scenarios using a 3D scanner app. Indoor scenes are evaluated from a reconstruction aspect, and geometric factors are considered. From the perspective of mobility, outdoor environments are analyzed, and factors determining the physical accessibility of building entrances are considered for evaluation. An indoor environment with two contiguous rooms is employed as a case study for indoor mapping efficiency analysis. In the context of mobile applications for people with disabilities, places like sidewalks and building entrances are particularly relevant. The authors highlight that the decreased range of acquisition, which is specified as 5 meters, is one of the primary limitations of Lidar in smartphones. As a result, the new customer sensors are more attractive to use in locations that are harder to access or are often obscured when employing car-based mobile mapping scanners. Although the sensor can be practical for 3D mapping indoor and outdoor environments, the authors stated that extra attention should be paid to acquisition planning to avoid large and complicated paths. These Lidar sensors have initially proven to help recognize ground features that are inclined, vertically, and horizontally.

Following these findings**, (Jakovljević and Taboada, 2022)** intended to test the Lidar sensor integrated into the iPhone 13 Pro. The objective was to assess the iPhone 13 Pro Lidar sensor's indoor mapping capability concerning mapping room geometries, including room lengths and their components (doors, windows), geometrical details, and mapping flat and curved surfaces. The iPhone 13 Pro and classic TLS (Faro Focus M 70) were tested in a rectangular-shaped room with 7.7 m x 3.9 m. In this test, the Sitescape app was used. The device was around 1 and 4 meters away from the scanned objects. The scanning process took about ten minutes. Both observations were conducted on the same day without moving any object from the room to ensure a fair comparison. The findings indicate that the iPhone 13 Pro performs well on flat, curved surfaces. It produces a reliable point cloud in extremely detailed scenes; however, the degree of noise rises when the object is homogeneous. The study supports the applicability of the iPhone Lidar device in the acquisition of point clouds and the production of 3D models of indoor areas since it allows for fast data acquisition and processing.

In the same concept, **(Chase et al., 2022)** employed an iPhone 13 pro for indoor mapping of a surveying lab room, including a control network with sub-millimetre geometric precision. An iPhone 13 Pro's accuracy was assessed to determine its relative (related to the device's geometric accuracy) and absolute (compared to the surveyed control) accuracies using Modelar's scanning app. A TLS survey was also implemented to compare outcomes from the two devices. The results demonstrated that Modelar's laser scanner app can achieve absolute accuracies of 3 cm horizontally and 7mm vertically and a relative accuracy of 3 cm. The Apple Lidar can be useful for creating datasets for projects like Building Information Modelling (BIM) in some circumstances, especially in areas with easily recognizable elements like large pipes, pillars, and columns.

Later, **(Zaczek and Kowalska, 2022)** performed an inventory of a building using the iPhone 13 Pro Lidar and the 3D Scanner App. The collected data was used to compare the accuracy of the device's Lidar technologies to that of a Z+F Imager 5006h accurate terrestrial laser scanner. The author aimed to determine whether the Apple iPhone 13 Pro and 3D Scanner App Solution can be utilized to conduct building and architectural inventories. A typical office room and a section of the theatre cloisters were used as test objects. Each device scanned These objects at once, while black-and-white checkerboards were set at varied heights for the registration. The CloudCompare software tools were used to examine and compare the data. The findings indicated that the Apple iPhone 13 Pro's embedded Lidar sensor offers a promising capability for building inventorying. However, the study concluded that smartphone scanning would not replace precise solutions based on conventional surveying or TLS. This is primarily due to the iPhone 13 Pro's accuracy, which delivered centimeter-level accuracy. So this type of sensor can be used for work of limited accuracy, such as visualization, instead of precise measuring techniques.

In 2023, the iPhone Lidar collected 3D forensic data from crime and crash scenes. **(Kottner et al., 2023)** captured two indoor scenarios: a mock-up crime scene and a garage, in addition to an outdoor scenario of a parked car using iPhone 13 Pro and the Recon-3D app. Each scenario was observed five times. This study aimed to put the iPhone 13 Pro and the Recon-3D app through their different tests in various settings to see if this technology helps document crime or accident scenes. According to the author's findings, data collecting for one scenario took less than two minutes. The sensor was quick and easy to use, enabling anybody to conduct 3D documentation at a crime or accident location. Recon-3D seemed to be a valuable tool for forensic experts overall. It allows the creation of 3D datasets with acceptable quality and accuracy compared to tape measures. Furthermore, the overall 3D representations of the scenes had little to no noticeable noise. They enabled the acquisition of comprehensive spatial information, particularly for high-resolution scans with a scan density of 1.0 mm. Finally, they stated that this sensor would help capture 3D data containing valuable and measurable information that might be lost or inaccessible after leaving and clearing the scene. It may also be beneficial in cases where evidence is rapidly deteriorating, such as liquids or changes caused by meteorological conditions (e.g. snow on a street).

Later, the innovative sensor's accuracy was evaluated by **(Abbas and Abed, 2023)**. The positional accuracy of the Lidar sensor embedded in the iPhone 12 Pro Max was examined outdoors, specifically targeting the scanning of building facades for preservation purposes. The assessment involved two accuracy tests, utilizing total station measurements as the reference ground truth dataset. The initial evaluation compared the accuracy of the Apple Lidar sensor with that of a static TLS sensor. The second test, however, focused on validating the MLS sensor's precision and level of detail (LOD) across different distances ranging from 0.25m to 5m, which is the maximum range of the Apple Lidar sensor. The results of both tests revealed that the iPhone sensor delivered a high level of accuracy at the millimeter scale. The MLS sensor's accuracy at close range was nearly identical to that of a TLS sensor. The results of the second test revealed an increase in the errors of the MLS measurements as distance increased, the coverage of the building facade within the 5m range was still substantial (greater than 0.25m), and the level of detail was superior at very close range.

5.2 The Deployment of Apple Lidar in Cultural Heritage

Some scholars have also employed Apple LiDAR in cultural heritage preservation because of its affordability, mobility, and ease of use. Apple LiDAR devices offer an alternative solution that reduces costs, reduces data acquisition, and facilitates the preservation of large, complex, and detailed historical buildings compared to traditional techniques.

(Murtiyoso et al., 2021) discussed the importance of sensor minimization in producing low-cost sensors, which is always important in historical projects with low resources. The low-cost feature is crucial since many cultural preservation organizations strive to compromise cost and geometric accuracy **(Murtiyoso et al., 2019)**. The authors present a preliminary assessment of the use of Apple Lidar for heritage preservation. Three distinct scenarios were evaluated using two different apps, Sitescape and Every point. These apps allow the iPad Pro to collect point clouds of small to medium-sized objects, outdoor building facades, and indoor mapping. In each of the three cases, the data collected with the Apple Lidar was compared to a TLS (FARO Focus X330) and close-range photogrammetry (CRP) (Canon EOS 6D DSLR camera) reference data sets. The data collection and processing time was short, and the geometric quality was acceptable. However, one of the significant concerns with the data produced by this system when it was used to document cultural heritage was the high degree of noise in the recorded point cloud. The authors recommend using static acquisitions in challenging conditions and reducing the acquisition's point density quality to enhance sensor real-time tracking.

(Spreafico et al., 2021) It has noted the sensor's low cost, as well as its flexibility, mobility, and short time required for data collection and processing, which makes it an appealing solution when compared to other range-based systems. The authors used the iPad Pro for two types of acquisitions: static acquisitions to examine sensor potentials and dynamic acquisitions to evaluate 3D point clouds. The test was conducted on an outdoor emergency stairway attached to a heritage building that represents a complicated geometry structure comprising various architectural parts and details. SiteScape app was chosen because of its ability to customize acquisition settings (point cloud density and acquisition mode). The iPad Pro was mounted on a tripod for static acquisition, which involved scanning a white vertical and planar wall from various distances in an indoor environment (1,2,3,4 meter). In the dynamic mode, the iPad Pro was handled by a user outdoors on a cloudy day, and two different resolutions were tested to verify the LOD in the same part of the test area. This was applied following a horizontal or vertical movement while walking steadily and slowly at 1 to 3 meters from the scanned surfaces. According to test results, the sensor can rapidly collect precise 3D point clouds with centimeter-level precision and accuracy suitable for 1:200 architectural rapid mapping (precision 2 cm, accuracy 4 cm). The sensor could capture data at six different resolutions, including two acquisition settings (max area and max detail) and three types (low, medium, and high). The iPad Pro generates point clouds with a density of 500 to 16000 points and fewer file sizes than TLS.

In 2022, the apple Lidar was used in archaeology by **(Cohen-Smith et al., 2022**) for the site's excavation work, which was a component of a larger set of earthworks related to land developments along Pukaki Creek, north and east of Auckland International Airport (New Zealand). The Polycam app was used on an Apple iPad Pro 11" 4th Gen to scan the excavated pits. The scanning process entailed moving the device around the various features while following the app's directions. Additionally, the app gave instructions regarding areas that were either missing or were not sufficiently documented from the scan on the screen in real-time. The pits were typically scanned in a few minutes and processed in 5–10 minutes. The result of the scanning of the large pits. The authors stated that it was a relatively simple technique for creating a precise plan representation of a site or specific features that could be fused with other, more traditional survey data. One of the most notable advantages of mobile devices is the flexibility to scan features closely, which proved very beneficial for recording small underground archaeological features. Subsurface features are usually a challenge for terrestrial and airborne Lidar scanning. The sensor and app's simplicity, speed, and affordability mean that most professional archaeologists can easily access the technology. Based on observations made at the pit site, it was demonstrated that this technology outperformed terrestrial sensors when recording small subsurface features and was more cost-effective than more costly technologies.

Later, **(Teppati Losè et al., 2022)** assessed the iPhone 12 Pro and iPad Pro for the cultural heritage application. The test was split into two stages: the first evaluated the sensor's performance and capabilities, and the second concentrated on using Apple Lidar in cultural heritage. The initial phase of experiments also involved static and dynamic acquisition modes to determine any differences in performance between the iPad Pro and the iPhone 12 Pro Lidar. Three different applications were used (Sitescape, 3D scanner, and Everypoint). Three different representational sizes were employed to evaluate Apple Lidar's performance in heritage documentation: sculpture, medium-scale room, and medium-scale outdoor building facades. Data for the ground reference was also collected. Scan recordings were made for TLS (Faro Focus3D X330) to produce 3D models for validation. The analysis showed that the iPad Pro and iPhone 12 Pro use the same Lidar sensor, consistent with **(Luetzenburg et al., 2021)** findings. The studies were conducted in shadowed and sunny weather using several object materials, which indicated that neither the illumination nor the surface had a high effect on the sensor performance. This study found that the iOS application affects the quality of the acquired data, particularly in terms of geometrical reconstruction precision and accuracy, the highest acquisition time, and lastly, the size of the acquired object. The authors claimed that the Apple Lidar sensor could be appropriately used to document small and medium-sized items (e.g., statues, historical artefacts, rooms, and so on) with an accuracy of a few centimeters and a high LOD's.

6. DISCUSSION

Through a comprehensive literature review, some studies have mainly focused on using this sensor for indoor mapping with a 3D mesh-based app. Still, there is a need to explore its potential in outdoor environments, given its fast data collection time and affordability compared to other sensors and to explore more about this sensor's behaviour and specifications. However, based on the author's findings from previous studies, we can derive a summary of the Apple Lidar scanning application in addition to some of the sensor drawbacks and specifications as follows:

6.1 Summary

The most relevant works from previous scholars that have been earlier discussed in this article are highlighted and summarized as follows:

Table 3.1 The Summary of the As-built Scanning Applications.

Author-Year	Apple Device	The Used App	Application	Summary Points
(Spreafico et al., 2021)	iPad Pro	Sitescape	Structure 3D mapping and Cultural heritage documentation	According to findings, the sensor can quickly capture trustworthy 3D point clouds appropriate for rapid mapping of structures at a scale of 1:200.
(Vogt et al., 2021)	iPad Pro	Heges	Testing small-sized objects	• The iPad Pro was unsuitable for scanning small objects like Lego bricks. • While the software and the device's hardware control the scan accuracy, external factors like shape, texture, color, and scanning movements all affect scan quality.
(Murtiyoso et al., 2021)	iPad Pro	Sitescape and Everypoint	Cultural heritage documentation	• The data collecting and processing process are faster, and the geometric quality is acceptable. • However, one of the main problems with this instrument for capturing cultural assets is the high degree of noise in the collected point cloud.

(Luetzenburg et al., 2021)	iPhone 12 pro and iPad pro	3D scanner and Every point	Geoscience	The iPad and iPhone LiDAR sensors are identical.
(King et al., 2022)	iPhone 12 Pro	-	Snow-depth estimation	The iPhone LiDAR was capable of reliably capturing daily changes in snow depth compared to snow ruler readings.
(Díaz-Vilariño et al., 2022)	iPad Pro	3D scanner	Indoor and Outdoor mapping	The sensor can be helpful for 3D mapping of both indoor and outdoor surroundings, but special consideration should be taken while planning the data collection to prevent long and difficult paths.
)Jakovljević and Taboada, 2022).	iPhone 13 pro	Sitescape	Indoor mapping	• The iPhone provides a fully integrated technology for speedy point cloud collection and immediate data transfer. • The iPhone 13 pro-LiDAR has a high potential for quick, simple mapping of indoor scenes with adequate accuracy for modeling, particularly considering the device's affordable price.
(Chase et al., 2022)	iPhone 13 Pro	Modular	Engineering Application	• The iPhone is constrained to lower-scale applications at only 5 meters. • The Apple lidar can be helpful when creating datasets for projects like Building Information Modeling (BIM), especially in areas with plainly recognized features.
(Cohen-Smith et al., 2022)	iPad Pro	polycam	Scanning of an excavation site	It was found that this technology performed better when recording small subsurface features than terrestrial sensors and was more cost-effective than costly technologies.
)Teppati Losè et al., 2022(	IPad Pro and iPhone 12 Pro	SiteScape, EveryPoint, and 3D scanner	Cultural heritage documentation	The Apple lidar sensor can be used appropriately to document small and medium-sized objects (e.g., sculptures, historical artefacts, rooms, and so on) with a centimetric level of accuracy and a high level of detail.
Zaczek and Kowalska, 2022)	iPhone 13 Pro	3D Scanner	Inventory work	The iPhone 13 Pro's integrated LiDAR sensor offers considerable potential for architectural inventorying.
Kottner et al., 2023	iPhone 13 Pro	Recon-3D app	Capturing 3D forensic data at crime and crash scenes,	The scanning procedure was straightforward and quick, allowing anyone to perform 3D documentation at a crime or crash site. In general, it appeared to be a good tool for forensic experts.

6.2 Drawbacks of Apple Lidar

According to the findings from previous literature, there are various drawbacks of the Apple Lidar sensor that can be summarized as follows:

1. **(Murtiyoso et al., 2021)** highlighted that the poor illumination condition of the object can cause a significant problem for the real-time registration algorithm. Additionally, as

with conventional TLS, the Apple lidar sensor has issues when exposed to shiny or light-absorbing materials such as marble.
2. External aspects, including lighting, reflectivity, texture, color, and shape, may also impact the scan quality, the user's movements and the distance from the target **(Vogt et al., 2021)**. Also, **(Kottner et al., 2023)** mentioned that some materials and surfaces generate gaps in the 3D point cloud, leading to misaligning data points or color distortions, especially highly reflective and transparent materials, such as bright or mirror-like surfaces and glass (e.g., car windows). In addition to black and dark materials.
3. This sensor is unsuited for scanning small objects **(Vogt et al., 2021)**.
4. The range limitation (maximum 5 m), storage capacity, and battery are some of the drawbacks of this sensor, which become more apparent while scanning larger areas **(Cohen-Smith et al., 2022)**.
5. When scanning an object for more than a few seconds, especially one with less discernible detail or sharp edges, or one that is noisy, like a carpet, the iPhone's tracking may drift, resulting in misaligned points **(Putch, 2022; Jakovljević and Taboada, 2022)**.
6. In direct sunlight, the point cloud's precision decreases, resulting in miss-aligned points and a drifting effect **(Jakovljević and Taboada, 2022)**.

6.3 Apple Lidar Pros

Here are some sensor pros and specifications derived based on scholar's findings, as well as an expected specification based on this sensor's behaviour:

1. The LiDAR sensors in the iPad and iPhone are identical because there were no differences between the iPad and iPhone LiDAR scanners regarding point density, the total number of emitted points, or focal length **(Luetzenburg et al., 2021).** However, **(Teppati Losè et al., 2022)** stated that there are a few notable variances in specifications. The iPad Pro has a larger screen, allowing for better real-time observation of the acquisition process; however, the iPhone 12 Pro is lighter, and the A14 Bionic chip performs better than the A12Z found on the iPad Pro.
2. The A14 Bionic chip and 16-core Neural Engine built into the iPhone 12 Pro boost its performance in terms of speed while also allowing it to save energy **(Teppati Losè et al., 2022)**
3. Apple's LiDAR employs a direct time of flight (DTOF) system where the distance measurement can be obtained by sending pulses towards objects and then rebounding them back to the sensor, providing 3D positioning **(Budisusanto et al., 2021; Luetzenburg et al., 2021; Spreafico et al., 2021; Teppati Losè et al., 2022).** A near-infrared (NIR) complementary metal-oxide semiconductor (CMOS) image sensor (CIS) for the SPADs is used with the LiDAR **(Spreafico et al., 2021; Teppati Losè et al., 2022).**
4. The LiDAR used in Apple devices has a receiver that is a single-photon avalanche diode (SPAD) and an emitter built of a vertical-cavity surface-emitting laser (VCSEL) that transmits laser pulses with a diffraction optics element (DOE) **(Luetzenburg et al.,2021; Spreafico et al., 2021; Vogt et al., 2021; Chase et al., 2022; Jakovljević and Taboada, 2022; Teppati Losè et al., 2022).**

5. The VCSEL transmits an array of 8*8 points, distributed evenly into 3*3 grids, resulting in a global matrix of 576 points **(Luetzenburg et al., 2021; Teppati Losè et al., 2022)**.
6. Unlike traditional laser scanners, which have one laser beam and a rotating mirror to deflect the laser beam around the scanned area, the iPhone LiDAR has no moving elements. Alternatively, it comprises thousands of lasers on a chip, with a laser assigned to each point in the LiDAR's field of view **(Jakovljević and Taboada, 2022).**
7. It can scan small objects, such as Lego bricks, but was shown to be ineffective when using an iPad Pro lidar sensor **(Vogt et al., 2021**). This is highly beneficial for applications that need a device to scan fine details, such as CH applications.
8. Apple lidar can produce a variety of essential data formats, like E57, PLY, LAS, obj, XYZ, STL and many others formats.
9. Some MLS systems, especially handheld MLS, use the SLAM algorithm. Apple lidar sensors may follow the same approach since the automatic registration of Multi-Scan in the Sitescape app relies on real-time localization **(Putch, 2022)**.
10. Apple does not currently offer the raw LiDAR depth data for various uses on iOS devices (i.e., iOS 14). Instead, a depth map is produced by combining the LiDAR depth data with the supporting color (RGB) data using artificial intelligence (AI) **(Vogt et al., 2021)**. It is possible to create colorized 3D models using both wide (main) and ultra-wide camera lenses **(Gollob et al., 2021)**.

7. CONCLUSIONS

The Apple LiDAR sensor represents a markable development in 3D mapping and the technological revolution. Integrating LiDAR technology in mobile devices has gained attention from researchers' communities. This article carried out a physical concept about the lidar technology in addition to an organized review of the literature, emphasising the potential applications of the novel Apple lidar sensor, particularly for indoor and outdoor 3D mapping and the preservation of cultural heritage. However, as this sensor's primary function was to enhance augmented reality (AR) experiences and enable 3D modelling of indoor spaces, most of these researchers employed it for indoor mapping, leading to a lack of studies on large-scale outdoor mapping. The presented literature leads to the conclusion that the significant characteristics of the apple lidar are its affordability and shorter observation times when compared to conventional surveying methods, photogrammetry, or industrial TLS sensors. The amount of research that has been undertaken to explore the performance of this sensor in numerous disciplines, in addition to its existence in the most recent Apple products, is a clear indication that it will continue to evolve. We may anticipate even more new and fascinating LiDAR applications and advancements in sensor specifications that fit the user's needs.

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Credit authorship contribution statement

Sahar F. Abbas: Investigations, methodology, discussion & writing – original draft preparation. Fanar M. Abed: Conceptualization, methodology, discussion, review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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