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Review on LiDAR technology

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Abstract The LiDAR (Light Detection And Ranging) technology has been in existence since the 1960s. The advancement in technology has made LiDAR a popular sensor nowadays. LiDARs are now used in the field of automation, agriculture, archaeology, and also quantifying various atmospheric components. The current manuscripts include the working of LiDAR, its types, history, and different applications of LiDAR. From LiDAR measurements, one can calculate the distance from different objects in space and draw the 3D digital representation of the area in front of LiDAR.

Keywords LiDAR · Scanning · Bathymetric

1 Introduction

Light detection and ranging (LiDAR) employs the method of sending laser light on to the target and measuring the reflected light back to recognize the variation in wavelength and arrival time of the reflected light. Sometimes it is not feasible to be physically present in an environment and measure things manually. For such measurements, LiDAR comes into the picture. The measurement is done by calculating the laser return times and their wavelengths. It generates precise, high quality, and sometimes even a three-dimensional map of the environment that it scans. The generated map of the area in focus, helps in its characterization and examination. A typical LiDAR system consists of a scanner, laser, and sometimes specialized GPS receiver as well. Other elements that are essential for data collection and analysis are optics and photodetectors. The LiDAR data scanned is generally stored in a file with an extension of ".las". This format is supported by the American Society of Photogrammetry and Remote Sensing (ASPRS). A new format with an extension ".laz" has been developed recently by LasTools. ".laz" is a highly compressed version of ".las". The output data derived from the scanned data are stored in a file with an extension of ".tif". This system is typically used by scientists and mapping professionals to examine the environment they are interested in. These LiDAR measurements are mostly used for airborne, mobile, and terrestrial applications.

LiDAR has been advantageous in many sectors including the agricultural sector, where LiDAR robots plant seeds, detected weeds along with automated spraying and fertilizer distribution which makes it easier to grow crops, fruits, and vegetables effectively. In Archaeology, LiDAR can be used to determine the features of the ground, examine the forest canopy, and to create a high-resolution model of an archaeological site to uncover the topography, which was not possible to detect earlier. In autonomous vehicles, LiDAR is used to detect and avoid obstacles so that it can easily navigate through the path using laser beams. LiDAR can be used to obtain rain clouds profile, measure winds, study aerosols and quantify various atmospheric components, which may prove to be useful information for determining surface pressure, greenhouse gas emissions, photosynthesis, fires, and humidity.

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2 History of LiDAR systems

The distance measurement using the light beam was used first time in the 1930s. To measure the distance searchlights were used. Light pulses were used to deter-

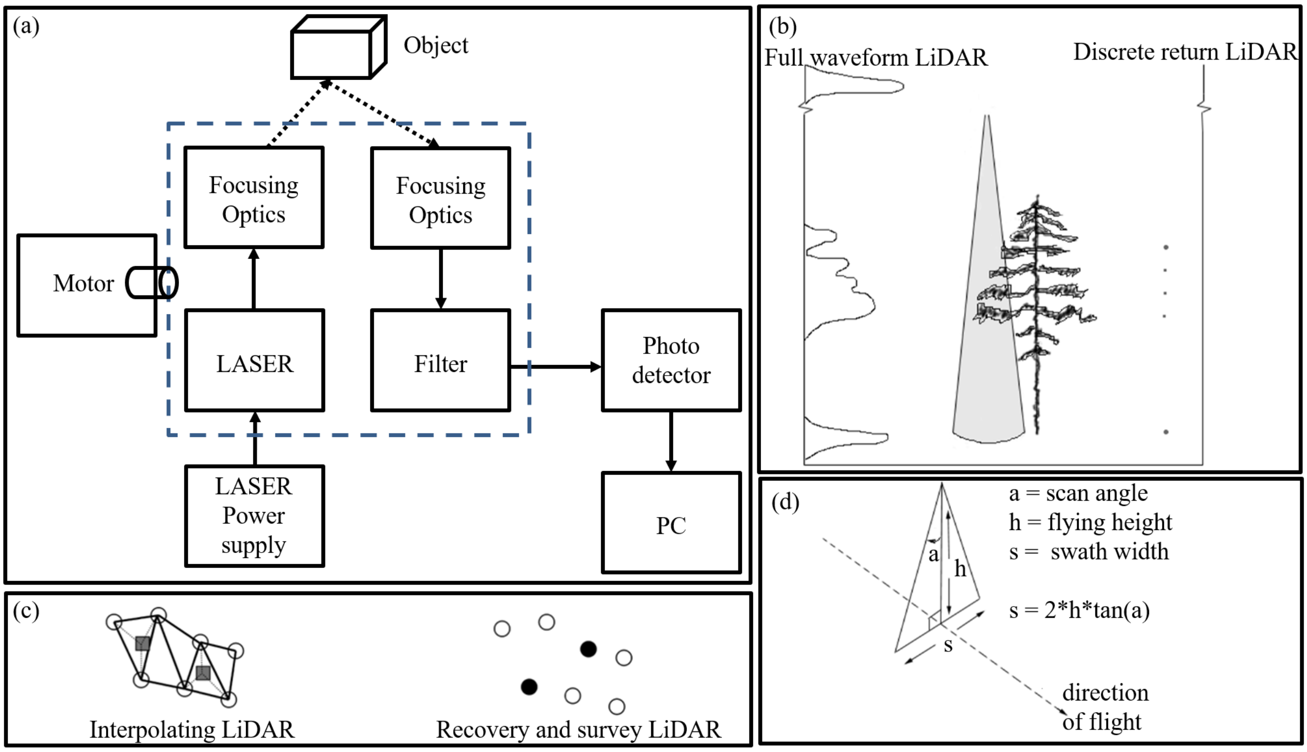

Fig. 1 (a) Operational block diagram of LiDAR. Power is passed on to the LASER using the LASER power supply. The LASER passes through the focusing optics and falls on the object. The reflected LASER light from the object passes through another focusing optics and a particular wavelength is filtered by the filter. The output of the filter is passed to the photodetector and then to a PC to examine or analyze the output. The whole system rotates with the help of a motor. (b) Differences between discrete return and full-waveform vertical sampling. A Discrete Return LiDAR records the individual points for the peaks in the wave from curve whereas a Full Waveform LiDAR records a distribution of returned light energy. (c) Linear interpolation of reference points introduces additional error in the observed LiDAR error, whereas, surveying the LiDAR point locations does not. (d) Swath width as a function of instrument scan angle and aircraft flying height

mine the height of clouds in the year 1938. Shortly after the invention of the laser in the year 1960, the LiDAR was invented to be used in airplanes. The first LiDAR system was introduced in 1961 by Malcolm Stitch, for the Hughes Aircraft Company. Initially, the LiDARs were used for tracking. The tracking was achieved using a combination of the imaging ability of laser and the ability to measure distance. LiDAR can measure distance by examining the reflected laser using appropriate sensors. At first, it was called Colidar, as an acronym for "Coherent light detecting and ranging". Using the original Colidar system, many new systems are derived, including laser rangefinders, laser altimeters, etc. Colidar system was first used on the land in 1963 and was called Colidar Mark II. Its main purpose was in the military. The term LiDAR was first coined in 1963. It was a combination of the words "light" and "radar". During the 1970s, NASA began laser-based remote sensing which focused on the airborne prototypes for subsequent LiDAR sensor deployment. Its main aim was to measure the properties of the ocean waters and atmosphere. It also helped to scan ice sheets and the forest canopy for topographic mapping. Since then, the scientific uses of LiDAR have been evolving. In the mid-1980s, there was a lack of reliable commercial global positioning system / inertial measurement unit (GPS/IMU). Hence there was a lot of research going on to find solutions for the sensor positioning system. This research went into the problem of finding the right backbone technology for imaging. However, the need for sensors in aerial photogrammetry was rapidly increasing which finally led to LiDAR research and development. LiDAR proved as the best sensor to work with aerial photogrammetry. However, accurate LiDAR imaging data were not possible to get, until the arrival of commercially available Global Positioning System (GPS) equipment and inertial measurement units (IMUs) in the late 1980s.

3 Working of LiDAR

The design principle behind LiDAR is the reflection of light. This principle is to shine a light beam on to a surface and calculate the time it takes to return to its

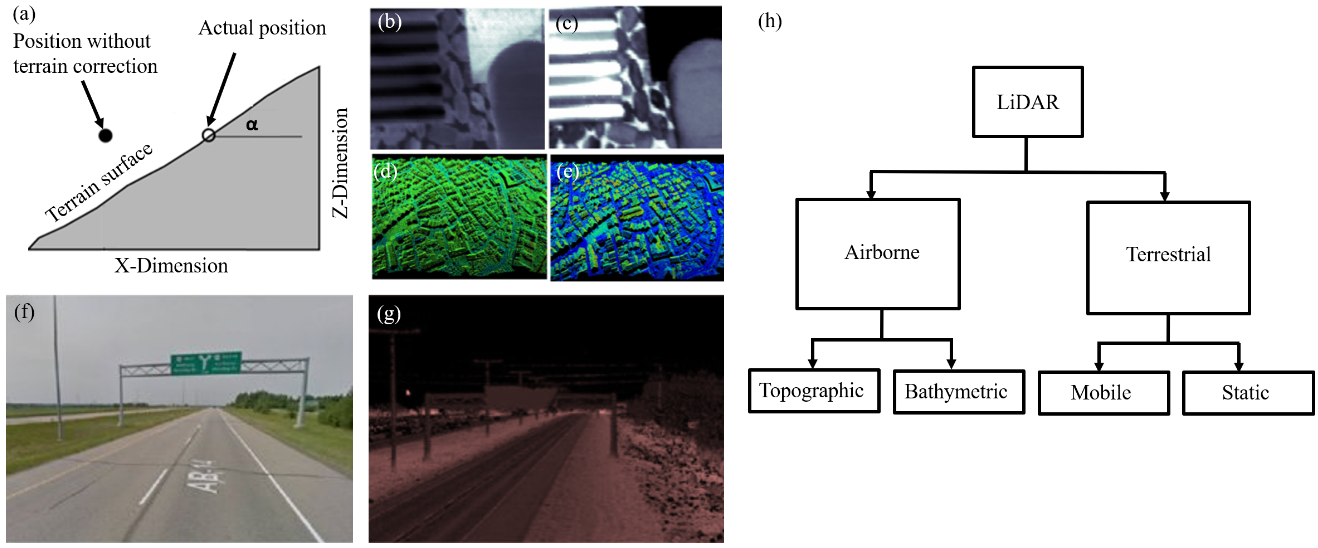

Fig. 2 Fig 2. (a) Illustration of the effects of terrain slope on observable elevation error. The location of the LiDAR point is at a considerable distance from the actual position of the terrain point. (b) Pulse width image produced by a LiDAR. (c) Intensity image as perceived by the LiDAR system. (d) An image produced by the LiDAR system focussing on the width (ns) (e) Amplitude centric image produced by the LiDAR system. An image of highway (f) and is corresponding LiDAR image(g). (h) LiDAR system classification. There are two major types of LiDAR systems. The first type is Airborne LiDAR which is installed in an aircraft or a helicopter. The Airborne LiDAR has two subtypes. The first one is Topographic LiDAR which used in forestry, urban planning, landscape ecology, etc. and the second one is Bathymetric LiDAR which is mostly used near coastlines, shores, and banks. The second type of LiDAR is Terrestrial LiDAR which used to survey highways and railways, manage facilities, create 3D models for spaces, etc. There are two subtypes in the Terrestrial LiDAR. The first one is Mobile LiDAR used to analyze road infrastructure, locate incoming road signs, light poles, etc and the second one is Static LiDAR, typically used in engineering, archaeology, mining, and surveying.

source. The LiDAR system sends laser light on to the target and measures the reflected light to see the variation in wavelength and arrival time of the reflected light. From these measurements, it can calculate the distance to draw the digital representation of the target. Since light travels at a very high speed, the calculation of the exact distance through LiDAR is very fast. The formula that the analysts use to calculate the distance is given in equation 1.

$$D = c\ (\varDelta T/2) \tag{1}$$

where,
D = The distance of the object
c = Speed of light
$\varDelta$ = Time required by the light to travel

The LiDAR system fires many laser lights on to the surface. The sensor on the system measures the time taken for the reflected light to reach the sensor. This goes on repeating until a complex map of the surface is constructed.

4 Types of LiDAR

There are two main types of LiDAR, namely airborne and terrestrial. Airborne LiDARs are designed in such a way that they point downwards and typically scans 180 degrees of solid angle. On the other hand, Terrestrial LiDARs mostly perform the horizontal scan and typically cover 360 degrees in 1-D or in 2-D. Airborne LiDAR systems are typically installed in an aircraft or a helicopter. The laser light from the LiDAR on the aircraft is emitted towards the ground which gets reflected and returns to the moving airborne LiDAR sensor. The airborne LiDARs are of two types, which are topographic and bathymetric. Topographic LiDARs are used to examine the surface, which can be used in forestry, urban planning, landscape ecology, etc. Bathymetric LiDARs are used for water penetration applications. They are typically used for examining elevation and water depth simultaneously. It is used for water penetrating but it is also used for examining elevation and water depth simultaneously. It is mostly used near coastlines, shores, and banks. A terrestrial LiDAR collects points with high accuracy to enable precise identification of objects. Typically terrestrial LiDARs are used to survey highways and railways, manage facilities, create 3D models for spaces, etc. Also, there are two types of terrestrial LiDAR mobile and static. In a mobile terrestrial LiDAR, the LiDAR system is mounted on a vehicle, train, or on the boat. In mobile LiDARs the point clouds are collected from a moving platform. Multiple sensors can

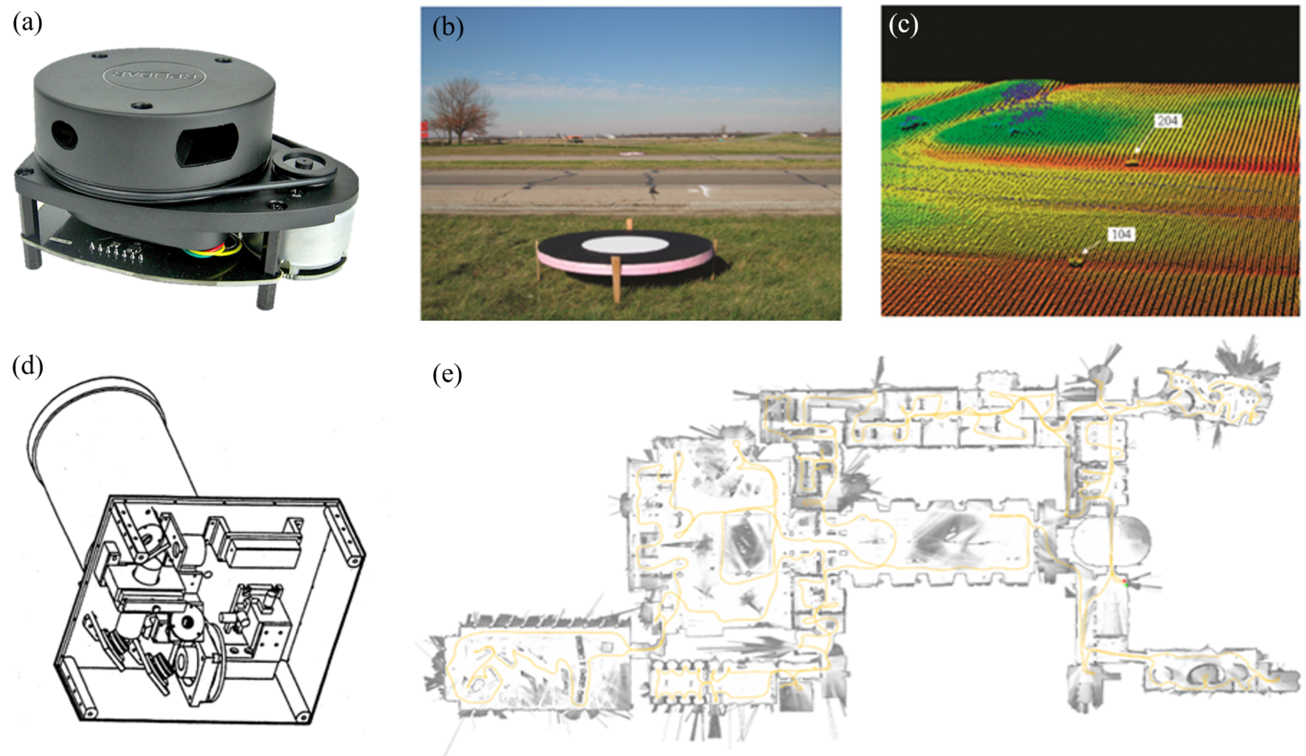

Fig. 3 Fig 3. (a) LiDAR A1M8 model it is most commonly used during development. It can rotate 360 degrees and plot 2D map (b)Airborn LiDAR target pair as an object to examine and correlate image produced by the LiDAR (c) Appearance of the LiDAR target pair in the LiDAR data produced (d) Transmitter and receiver unit of a Micro Pulse LiDAR (MPL) system (e) Cartographer map of the 2nd floor of the Deutsches Museum obtained using LiDAR scans.

be installed on a single platform. It can be used to analyze road infrastructure, locate incoming road signs, light poles, etc.In a static LiDAR, the sensor is usually mounted on a tripod mount. Static LiDARs can collect LiDAR point clouds inside buildings as well as exteriors. This type of LiDAR is typically used in engineering, archaeology, mining and surveying.

LiDARs can also be classified on the basis of the dimensions as 1D, 2D, and 3D LiDAR. The working principle of each of the LiDAR is the same, but the difference lies in the usage of point and shoots mechanism, a scanning mode system, and the number of laser beams used. In a 1D LiDAR, a still laser beam is used that measures the distance between an obstacle and the scanner on one axis of dimension. In a 2D LiDAR, only one laser beam is required. The LiDAR will pulse based on a spin movement and collect horizontal distance to the targets for getting data on the X and Y axes. It rotates in 360 degrees or 180 degrees as per application. The rotation is carried with the help of a DC motor connected to the pulley system. A 3D LiDAR is almost the same as the other two LiDAR systems, but numerous laser beams spread out in different directions to get data on X, Y, and Z axes data. Each laser beam has a predefined angle delta with other beams.

LiDAR can also be classified into three types based on backscattering. These types are Rayleigh LiDAR, Mie LiDAR and Raman LiDAR. In some cases, LiDAR can be also be classified in one another way. In this classification, LiDAR has two types which are Coherent and incoherent LiDARs. Coherent LiDARs are based on phase sensitivity and Incoherent LiDARs are based on amplitude measurement.

5 Literature review

Micro Pulse LiDAR was developed by Spinhirne *et al.* [1]. This system was an eye-safe, compact, solid-state LiDAR for profiling atmospheric cloud and aerosol scattering. The intended applications of this Micro-pulse LiDAR are scientific studies and environmental monitoring which could allow the user to develop full time, unattended measurements of the cloud, and aerosol height structure. The LiDAR was used by Lim *et al.* [2] for the processing of physical geography. This system was used to directly retrieve the forest attributes, such as canopy height from LiDAR data. Direct retrieval of canopy height provided opportunities to model above-ground biomass and canopy volume. Access to the vertical nature of forest ecosystems also offered new opportunities for enhanced forest monitoring, management, and planning.

Hodgson *et al.* [3] showed empirical assessment and error budget of accuracy in Airborne LiDAR derived elevation. In this research, an accuracy assessment of a recently acquired LiDAR derived data set was conducted as part of a village wide large scale mapping effort for Richland village in South Carolina. Also, terrain data was acquired simultaneously using an Optech ALTM (Airborne Laser Terrain Mapper) 1210 system.

The random modulation CW LiDAR was developed by Takeuchi *et al.* [4]. In this work, LiDAR is used for the profile measurement of a continuous environment quantity. This included not only air pollutants, cloud and fog, but also temperature, humidity, and wind vectors. The LiDAR echo was considered as the response function to an interrogative input signal. It reflected the spatial distribution profile of medium density. Two methods have been used to obtain the response function, which are impulse response and pseudorandom code modulation respectively.

Means *et al.* [5] worked on predicting forest stand characteristics with Airborne scanning LiDAR. In this work, they investigated the feasibility of predicting characteristics of forest stands with LiDAR data in a university-industry partnership. LiDAR lends itself well to such applications because it allows direct measurement of important structural characteristics of height and canopy closure. The study found that LiDAR data can be used to predict the stand characteristics of height, basal area, and volume quite well. This research showed that LiDAR data can be used to estimate stand characteristics over large areas or entire forests.

Fernald *et al.* [6] used LiDAR to determine the aerosol height distributions. The research showed that without any data from supporting experiments, the system must be well-calibrated, and the physical makeup of the scatterers themselves should be known. Their work shows how these difficulties may be avoided by supplementing the LiDAR observations with one additional piece of information, namely, the transmittance of the layer in question. Their primary purpose was to present a complete analytic solution to the LiDAR equation for conditions where both molecules and aerosols contribute significantly to the problem. The solution is then applied to LiDAR observations.

Mallet *et al.* [7] worked on a Full-waveform topographic LiDAR. They presented a survey of the literature related to Airborne laser scanning (ALS). The technique is an active remote sensing technique providing range data like 3D point clouds. The emphasis was on the new sensors called full-waveform LiDAR systems. Full-waveform LiDAR data can give more control to an end-user in the interpretation process of the physical measurement and provide additional information about the structure and the physical backscattering characteristics of the illuminated surfaces. Their work also described the theoretical principles of full-waveform airborne laser scanning.

Hunt *et al.* [8] worked on the performance assessment of CALIPSO LiDAR and described it. Their work provided background material for a collection of Cloud Aerosol LiDAR with Orthogonal Polarization (CALIOP) algorithm research.

The work on LiDAR Odometry and Mapping in Real-time was done by Zhang *et al.* [9]. Their work proposed a real-time method for odometry and mapping using range measurements from a 2-axis LiDAR moving in 6-DOF. The problem was crucial to address because the range measurements are received at different times, and errors in motion estimation can cause misregistration of the resulting point cloud.

Andersen *et al.* [10] used LiDAR data to estimate forest canopy fuel parameters. In this work, regression analysis was used to develop predictive models relating a variety of LiDAR-based metrics to the canopy fuel parameters estimated from inventory data collected at plots established within stands of the varying condition within Capitol State Forest, in western Washington State. A cross-validation procedure was used to assess the reliability of these models. The work showed that LiDAR-based fuel predictions can be used to develop maps of critical canopy fuel parameters over forest areas in the Pacific Northwest.

Sun *et al.* [11] worked on Modeling LiDAR Returns from Forest Canopies. A three-dimensional (3-D) model was developed and implemented to understand the relation between canopy structure and the LiDAR return waveform. Detailed field measurements and forest growth model simulations of forest stands were used to parameterize this vegetation LiDAR waveform model. In the model, the crown shape of trees determined the vertical distribution of plant material and the corresponding LiDAR waveforms.

The role of LiDAR in sustainable forest management was demonstrated by Wulder *et al.* [12]. In this work, the status of LiDAR remote sensing of forests, including issues related to instrumentation, data collection, data processing, costs, and attribute estimation were presented. The information needs of sustainable forest management provide the context within which the future opportunities for LiDAR and automated data processing is considered.

Using large-footprint LiDAR, Drake *et al.* [13] worked on estimating tropical forest structural characteristics. The primary objective of this study was to test the ability of large-footprint LiDAR instruments to recover forest structural characteristics across a spectrum of land cover types from pasture to secondary and primary tropical forests. The results confirmed the ability of large-footprint LiDAR instruments to estimate important structural attributes, including biomass in dense tropical forests, and when taken along with similar results from studies in temperate forests, strongly validated the Vegetation Canopy LiDAR (VCL) mission framework.

Csanyi *et al.* [14] worked on the improvement of LiDAR data accuracy Using LiDAR specific ground targets. Their work proposed the use of LiDAR - specific ground targets to support applications that require extremely high, engineering scale mapping accuracy, such as transportation corridor mapping. Simulations were performed to determine the most advantageous LiDAR target design and targets were fabricated based upon the simulation results. They described the optimal LiDAR target design, the target identification algorithm, and detailed performance analysis, including the investigation of the achievable LiDAR data accuracy improvement using LiDAR -specific ground control targets in the case of various target distributions and flight parameters.

The work on compact eye-safe LiDAR systems was done by Spinhirne *et al.* [15]. They surveyed a new technology for compact, eye-safe LiDAR. Advances with solid-state lasers and detectors permitted efficient LiDAR designs that met the requirements for full-time atmospheric monitoring. A micropulse LiDAR is an approach that employs kHz pulse rate and YLF lasers and micro Joule pulse energies at visible wavelengths. Eye safety is an essential factor and is obtained by beam expansion.

Hess *et al.* [16] worked on real-time loop closure in 2D LiDAR SLAM. Building a portable capture platform necessitates operating under limited computational resources. They presented the approach used in the backpack mapping platform which achieves real-time mapping and loop closure at a 5cm resolution. To achieve real-time loop closure, a branch-and-bound approach is used for computing scan-to-submap matches as constraints.

Small-footprint airborne LiDAR was used by Zimble *et al.* [17] to characterize vertical forest structure.

Their work was based on a vertical forest structure which is difficult to quantify and yet is an important component in the decision-making process. The work also investigated the use of LiDAR data for classifying this attribute at landscape scales for inclusion into decision-support systems. Analysis of field- derived tree height variance demonstrated that differences between single-story and multistory vertical structural classes could be detected.

Deems *et al.* [18] wrote a review on LiDAR measurement of snow depth. They estimate light penetration depth by wavelength to estimate radiative transfer error contributions. Work presented a review of LiDAR mapping procedures and error sources, potential errors unique to snow surface remote sensing in the near-infrared and visible wavelengths, and recommendations for projects using LiDAR for snow-depth mapping.

The work on finding out the methodology for error analysis and simulation of LiDAR aerosol measurements was done by Russell *et al.* [19]. Their work presented a methodology for objective and automated determination of the uncertainty in aerosol measurements made by LiDAR. The methodology is based on standard error-propagation procedures, a large database on atmospheric behaviour, and considerable experience in processing LiDAR data. It yields algebraic expressions for probable error as a function of the atmospheric, background lighting, and LiDAR parameters.

Ni-Meister *et al.* [20] worked on modeling LiDAR waveforms in heterogeneous and discrete canopies. This study explored the relationship between laser waveforms and canopy structure parameters and the effects of the spatial arrangements of canopy structure on this relationship through a geometric optical model. Studying laser waveforms for such plant canopies is needed for the advanced retrieval of 3-D canopy structure parameters from the vegetation canopy LiDAR (VCL) mission.

6 Applications of LiDAR

LiDARS are used in various fields ranging from agriculture to robotics. Few of the LiDAR applications as per field are mentioned below:

6.1 Agriculture

LiDAR robots are used in seed and fertilizer dispersion, and scanning the crops for the presence of weeds. It also determines where to spray the fertilizer according to the location of the farmland. Detection of insects can also be done using LiDAR.

6.2 Archaeology

LiDAR can be used to determine the features of the ground as well as to examine the forest canopy. It can be used to create a high-resolution model of an archaeological site to uncover the topography which was not possible to detect earlier.

6.3 Autonomous vehicles

LiDAR is used in autonomous vehicles to detect and avoid obstacles so that it can easily navigate through the path using laser beams.

6.4 Atmosphere

LiDAR can be used to profile clouds, measure winds, study aerosols, and quantify various atmospheric components which may prove to be useful information for determining surface pressure, greenhouse gas emissions, photosynthesis, fires, and humidity.

6.5 Law enforcement

Police use LiDAR speed guns to measure the speed of passing vehicles and control speed. It is also used in forensics to help in crime site investigation for determining the placement of objects, blood examination, etc.

6.6 Military

LiDAR systems are used to collect information to identify targets, such as tanks. They are used in the Airborne Laser Mine Detection System (ALMDS) for countermine warfare by Areté Associates. To address the presence of bio-threats in aerosol form over critical indoor, semi-enclosed, and outdoor venues such as stadiums, subways, and airports, short-range compact spectrometric LiDAR based on Laser-Induced Fluorescence (LIF) would be used. It makes possible rapid detection of a bioaerosol release and allows for timely implementation of measures to protect occupants and minimize the extent of contamination because of the near real-time capability of LiDAR systems.

6.7 Mining

LiDAR systems are used for the calculation of ore volumes by periodic scanning in areas of ore removal, then comparing surface data to the previous scan. LiDAR is also used for obstacle detection and avoidance for robotic mining vehicles such as in the Komatsu Autonomous Haulage System (AHS) used in Rio Tinto's Mine of the Future.

6.8 Robotics

LiDAR is used in robotics for the scanning of the environment as well as to object recognition. It enables the safe landing of robots and manned vehicles with precision.

6.9 Surveying

Airborne LiDAR sensors are used for the remote sensing field. They are used to create a DTM (Digital Terrain Model) or DEM (Digital Elevation Model).

6.10 Forestry

LiDAR systems prove to be helpful in the improvement of forestry management. They are used to calculate individual tree heights, crown width, and crown diameter. LiDAR can also be used to estimate total plot information such as canopy volume, mean, minimum and maximum heights, and vegetation cover estimates.

7 Results and discussions

Table 1 shows the comparison of different LiDAR technologies reported in the literature. Pulse energy varies from 1 J to 4 J. The wavelength has a high range which starts at as low as 514 nm (visible light) and goes on till 1064 nm. The accuracy obtained with LiDAR scanning is usually around 90 % and it can vary from as low as 59 % .to as high as 99.10 %. The RMSE can be as low as 3.4c m and it can go up till 100 cm. The distance range of LiDAR can vary from 3.03 m to 58 m in value.

8 Conclusions

LiDAR is a device that throws light and measures back the time it requires for reflection. It is now more than five decades-old technology. Earlier it was used to measure the distance from the satellite. Nowadays LiDAR systems are very popular in autonomous vehicles where the LiDAR is used as the main sensor to determine the obstacles. Along with that, there are multiple applications of LiDAR especially the Airborne LiDAR systems where the territory mapping is done. Airborn LiDARs are used especially in the field of environmental studies for the prediction of rain or in the field of sea depth mapping or to navigate ships, etc. Pulse LiDARs can also be used in archaeology. We found that the pulse energy of LiDAR could be very low and that pulse energy basically decides the distance till which the LiDAR can

Table 1 Comparison of different LiDAR Technologies

	Pulse energy	Wavelength	Accuracy	RMSE	Distance
Spinhirne *et al.* [1]	2 μJ	–	–	–	–
Lim *et al.* [2]	–	1064 nm	90 %	100 cm	–
Hodgson *et al.* [3]	–	–		17.2 cm	–
Takeuchi *et al.* [4]	1 J	514.5 nm	–	–	–
Means *et al.* [5]	–	–	93 %	73 cm	–
Fernald *et al.* [6]	–	–	70 %	–	–
Mallet *et al.* [7]	–	1064 nm	–	–	–
Hunt *et al.* [8]	–	532 nm	–	–	–
Zhang *et al.* [9]	–	–	99.1 %	–	58 m
Sun *et al.* [11]	–	–	–	–	3.88 m
Wulder *et al.* [12]	–	1064 nm	–	–	–
Drake *et al.* [13]	–	–	59 %	3.84 cm	–
Spinhirne *et al.* [15]	4 μJ	523 nm	–	–	–
Hess *et al.* [16]	–	–	93 %	–	–
Zimble *et al.* [17]	–	–	83 %	–	–
Deems *et al.* [18]	–	532 nm	–	–	–
Russell *et al.* [19]	1 J	690 nm	–	–	–
Ni-Meister *et al.* [20]	–	405 nm	–	–	3.03 m

throw and receive back the signal. Pulse energy can go as high as 1J. For a typical LiDAR system mean square error lies in few centimeters. For precise LiDAR systems could be up to micrometer. The accuracy of LiDAR typically should cross 90 % and for critical applications like autonomous vehicles, it should be more than 95 %. There are LiDAR systems available which can go up to 99.9 % accuracy at the compromisation of the cost. The LiDAR wavelength can be in the visible light transmission range i.e. 400 to 700 nm but preferred LiDAR range is 1064nm which is in the infrared range. Overall, with the low-cost LiDAR systems available in the market, we expect the trend in LiDAR as a sensor will increase exponentially in recent future, we will see more than half of the automation being run on LiDAR systems. LiDARs are not as costly as RADARs but have to save accuracy, So the LiDAR technology is the future.

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