The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLIII-B2-2022
XXIV ISPRS Congress (2022 edition), 6–11 June 2022, Nice, France

POINT CLOUD ACQUISITION TECHNIQUES BY USING SCANNING LIDAR FOR 3D MODELLING AND MOBILE MEASUREMENT

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KEY WORDS: Laser Scanning, LiDAR, Point Cloud, 3D Modelling, Mobile Mapping, Beam deflection

ABSTRACT:

Laser scanners collect three-dimensional spatial data of an imaging area in a very short time with high point density. The laser scanners can be classified by different aspects, such as multi beam, single beam, spinning, solid state, single or multi returns, short or long range, and field of view angle. The mapping industry usually looks for range, accuracy, point density, and measurement speed higher while cost, error, energy consumption and weight lower instruments. Particularly, developments in LiDAR photon imaging techniques have enabled laser scanning to be used in three-dimensional modelling, motion detection, autonomous vehicle and mobile measurement. The distance from the instrument to the scan point is measured by the pulse or phase-shift method in laser scanners. The scan beam is directed at a certain angle so that the imaging area can be measured in arrays of points. The orientation of the beam is provided as mechanically in some scanners, and by an opto-electronic mechanism in others. Moreover, some scanners use multiple 2D LiDAR planes for three-dimensional scanning. A mobile three-dimensional measurement can be performed by using multi-beam scanners integrated with the other related sensors. The high performance of the scanners is possible with knowing their measurement properties and technical specifications. In this study, LiDAR techniques, that perform scanning measurements by oriented beam, were investigated and their technical features were examined.

1. INTRODUNTION

Thanks to the advantages they provide, terrestrial laser scanners are widely used for purposes such as object modelling and topographic surveying (Wang and Li, 2020; Dora and Murphy, 2017; Hayakawa et al. 2016). Terrestrial laser scanners are also used for ground-based static or mobile measurements. The integrated use of laser beams with sensors such as GPS and IMU has enabled mobile 3D measurement (Yadav et al., 2017; Mandlburger et al., 2015). Terrestrial mobile LiDAR on vehicles is used in the creation of 3D models of urban areas and corridor mapping (Xia and Wang, 2018).

Surrounding multi-beam LiDAR (MBL) in a compact form is a favorite for robotics, mapping, security, driver assistance, and autonomous navigation. This sensor provides distance and calibrated reflectance measurements at all rotational angles (Alsadik, 2020b). Solid-state LiDAR technology, which has no or fewer moving parts, is very promising for both automotive and industrial applications. The performance of its OPA-based solid-state technology is carrying them towards relevant use cases for internet-of-things and mobility applications. In order to generate a 3D image from the measurement data of a 2D LiDAR sensor, the standard outgoing data must be accompanied by the mechanical application point of the sensor in the chosen coordinate system. The mechanical multi-layer LiDAR (MLL) offers higher scanning speeds to capture 3D data. (Weber, 2018).

Static scanners have a single APD imaging sensor to convert the reflected light radiation into digital code. The mobile scanning is done by using multi beams in the form of a plane that has line based APD sensor array, and integrated with sensors of GPS and IMU. Such laser scanners are widely used in autonomous vehicles and mobile mapping. In this study, LiDAR techniques for measuring point clouds in the form of scanning were examined.

2. BASICS OF LIDAR MEASUREMENT

The basic principles in laser scanners are to determine the distance and line direction of a scan point. The light reflected from the object is converted into digital codes to display and record the 3D location and reflectance of the measured scan point. The range can be estimated from known light speed and the time-of-flight of the laser pulse using direct or indirect methods. In beam guiding systems, the beam direction is expressed by the angles made in the horizontal and vertical planes of the coordinate frame. Measuring a scan point distance is defined as 1D, and in addition, measuring the beam direction in a defined plane along with the distance is defined as 2D LiDAR. By measuring the elevation angles of 2D LiDAR plane, the LiDAR provides a third information in addition to distance, and location in defined instrument based xyz coordinate system, and called 3D LiDAR. The light deflection and scanning techniques for 3D LiDAR are given on Figure 1.

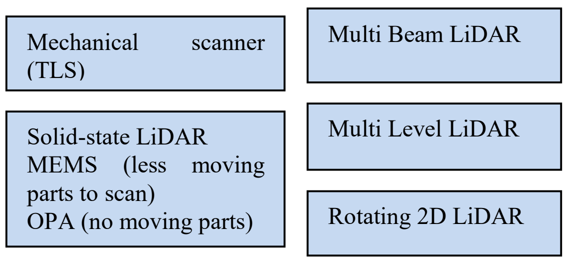

Figure 1. 3D LiDAR light deflection and scanning techniques

The laser scanner also records the intensity of the reflected light. The light intensity is highly dependent on surface reflectance properties. The colour and material properties of the

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measured surface affect the reflectance ratio. The high reflectance surface can be measured from distances away. The LiDAR maximum range is usually given by the reflectance ratio of the object surface. The range measurement accuracy is also proportional to the reflectance ratio. The multi-return property of the LiDAR instrument enables them to detect multi-depths in a single light direction. If the laser spot is larger than the measuring object, a part of the light will be reflected from the first near object and another part will be reflected from the surface behind it. This effect might occur multiple times in the same light direction. It is important to determine whether the measured value is part of the application or whether it should be discarded, e.g., due to a part falling across the field of vision. The receiver detector triggers when the incoming pulse reaches a set threshold, thus measuring the time-of-flight. The received laser pulse can be evaluated as measurement data in different manners, such as from the most significant return, from the first and last significant return, or from all returns which are above the threshold. It is useful to remove the error caused by rain, snow, and dusts on the imaging area. Or, it is evaluated for height detection of threes, in aerial measurements. Scanning LiDAR can use up to five returns. The 3D position accuracy of the scan point is largely related to the range, angular precision, beam divergence, reflection angle, and intensity of the reflected beam.

3. 3D LASER SCANNING

In scanning with a single beam, the laser beam is directed in particular step, as horizontally and vertically to measure details in the field of view. The laser scanners are collected in five groups according to the techniques used in beam directing. These are mechanical LiDAR (TLS), solid-state LiDAR of micro electromechanical systems (MEMS) and optical phased array (OPA) scanners, MBL, MLL, and rotating 2D LiDAR. MBL rotates around themselves with a multi-beam set (channels) and scan 360 degrees. 3D point clouds are also measured by rotating 2D LiDAR plane. The field of view is measured in the form of a series of points in homogeneous density consisting of rows or columns. The mechanical scanners are usually exploited for static measurements. Mobile measurements can be made with solid-state LiDAR, MBL, MLL or rotating 2D LiDAR scanners in a very high measurement speed.

3.1 Mechanical LiDAR (Terrestrial Laser Scanner)

3D coordinates (x,y,z) are calculated from the polar coordinates (range and direction angles) of the scanning beam. In addition, the intensity (I) of the received light is recorded for each scan point. The pulse method or AMCW phase difference (phase-shift) methods are used for range measurement. TLS using the pulse method can measure up to 6 km, and is suitable for surveying of land topography. For the TLS using the phase difference method, the measuring distance is shorter, around 800 m, but the accuracy is higher than the pulse based LiDAR. The measurement accuracy is around 5-10 cm at 1 km in the pulse method, while it is 1.5 cm at 1 km in the phase shift method. The measurement speed in the phase shift scanner is relatively higher than the pulse time scanner (see Table 1).

The beam is directed by an oscillating or rotating mirror to measure the details in the field-of-view (FoV) as a series of points in terrestrial laser scanners (TLSs). The scanning principle is changing according to beam deflection unit. The frame scanner, which has a fixed scanning head, uses two scanning mirrors to orient the scan line, and measures points as rows or columns. They have limited FoV e.g. 40º(H)x40º(V). Hybrid scanners use an oscillating or rotating polygonal mirror for beam deflection. They have a horizontal FoV of 360º and limited vertical FoV, for example, 60º (e.g. RIEGL VZ-4000). The panoramic scanner uses a flat rotating mirror. They have 360º horizontal FoV and around 320º vertical FoV (e.g. Z+F IMAGER 5006). They are especially useful in scanning indoors, since the whole space around the scanner can be captured from a single station. They typically use AMCW to range measurements (Reshetyuk, 2009).

TLS contains a large number of mechanical parts. It is very difficult to put these parts together in accordance with the mathematical model. Therefore, these scanners contain measurement errors caused by the structure of the system. The moving parts must be protected against vibrations and impacts so that their positioning is not impaired. However, solid-state LiDAR and MBL scanners have fewer moving parts, and proper for mobile mapping.

3.2 Solid-State LiDAR

The FoV 3D data is scanned by an oriented LiDAR line. More recent examples of solid-state LiDAR sensors incorporate technologies like MEMS or beam steering that can manipulate the laser beam to scan a much wider FoV than a typical ToF sensor. In the same cases, these LiDAR sensors can capture up to a 270° horizontal field of view. These solid-state sensors have no or less moving parts, which makes them less expensive and proper than a typical mechanical scanning LiDAR sensor.

3.2.1 Micro-Electromechanical Systems (MEMS) Scanner

The scan light in MEMS is guided by mirrors with a diameter of several millimetres. The mirrors can be oriented along two defined axes, and are guided by pre-programmed electronic signals. The tilt angle of the mirror varies when applying a signal, so the emitted light beam is modified to measure a specific point in the scene. In this way, the beam is directed so that the image area is scanned. Due to the structure of the system, these mirrors may be subject to deformation in static or working conditions. The design of this type of scanner is based on scanning area size, measuring distance, power consumption and measurement speed. (Gorecki and Bargiel, 2021). Their measurement distance is short (Table 2). It is usually used in automotive, machine vision and laser microscopes. Hamamatsu Corporation produces MEMS which has different configurations (Hamamatsu, 2021).

3.2.2 Optical Phased Arrays (OPA) scanner

OPAs are an emerging technology made of arrays of closely spaced (about 1μm) optical antennas which radiate coherent light in a broad angular range. Distance measurement is carried out directly by time of flight. The laser beam is split into micro-wavelength rays and directed. The beam is steered by the microwave arrays controlling the relationship between the receiving antenna arrays by balancing them (Table 2). OPA is a fast and sensitive scanning technique. OPA scanners are solid-state and contain a few moving parts, and are unaffected by vibrations. OPA components are based on mechanical control, such as motor-driven rotating collimation mirrors. The mechanical beam steering provides high efficiency and a relatively large scanning angle, through mechanically moving parts such as a gimbal. The bulky mechanical steering approach is less preferred due to acceleration, temperature, and vibration (Guo et al., 2021).

OPA technology enables very fast scanning (100 kHz) with low beam divergence and a wide FoV angle. A high-power and low-divergence beam is needed to accurately resolve a scene. Detecting a 10 cm object at 100m requires an OPA steering at a wavelength of 1µm with a circuit consisting of at least 1,000 antennas, each spaced 1µm apart. The OPA scanning provides a highly reliable and cost-effective 3D LiDAR solution that is important for the automotive industry. It is used for mobile mapping with ground vehicle or UAV.

The OPA can be implemented in the visible, near-infrared, and mid-infrared spectral ranges. The main performance parameters are field-of-view, beam width, side suppression, modulation speed, power consumption, and scalability.

Table 1. Technical specifications of mechanical laser scanners.

Company/ Product	**Laser wavelength**	**FoV (HxV)**	**Range measurement technique**	**Max. range**	**Range accuracy**	**Scanning rate**	**3D point accuracy**
Leica/BLK360	830nm	360°x300°	Phase-shift	60m	7mm@20m	360000 pts/sec	8mm@ 20m
Leica/RTC360	1550nm	360°x300°	Phase-shift	130m	0.5mm@20m	2000000 pts/sec	5.3mm@40m
Leica/ScanStationP40	1550nm	360°x290°	na	270m@%34	1.2mm+10ppm	1000000 pts/sec	6mm@100m
Leica/ScanStationP50	1550nm	360°x290°	na	1km@%80	1.2mm+10ppm	1000000 pts/sec	8” ang.res.
Z+F/IMAGER 5016	1500nm	360°x320°	Phase-shift	365m	1mm + 10ppm	1100000 pts/sec	0.004° ang.res.
RIEGL/ VZ-6000	NearInf	360°x60°	Pulsed	6000m@%90	15mm@150m	222000 pts/sec	0.0005° ang.res
RIEGL/VZ-4000	NearInf	360°x60°	Pulsed	4000m@%90	15mm@150m	222000 pts/sec	0.0005° ang. res.
RIEGL/VZ-400i	NearInf	360°x100°	Pulsed	800m@%90	5mm@100m	500000 pts/sec	0.0007° ang. res.
FARO/Focus 350 Plus	1550nm	360°x300°	Pulsed	350m@%90	1mm@25m	2000000 pts/sec	3.5mm@25m
OPTECH/Polaris	1550nm	360°x120°	Pulsed	2000m@%90	5mm@100m	2 Mhz	80µrad ang. res.
Topcon/GLS-2200	1064nm	360°x270°	Pulsed	500m@%90	3.1mm@150m	60000pts/sec	1mm@150m
Trimble/TX8	1500nm	360°x317°	Pulsed	340m@%90	<2 mm	1000000 pts/sec	80µrad ang. res.
PENTAX/S-3180V	na	360°x320°	Phase-shift	180m@%80	<1 mm	1016000 pts/sec	0.0007° ang. res.
MAPTEK/SR3	na	360°x130°	Pulsed	600m	4mm	200kHz	na
GVI/LiPod	903nm	360°x30°	Pulsed	100m	3cm	600kHz	5cm

Table 2. Technical specifications of solid-state LiDAR instruments.

Company/ Product	**Laser wave-length**	**Channel #**	**Light orienta-tion**	**Max. range**	**Scanning rate**	**FoV**	**Angular resolution**	**Accuracy**
Velodyne/Velarray M1600		8	MEMS mirror	30m	na	32°(V)	na	na
Hesai/PandarGT-L60	1550nm	64	MEMS mirror	300m	20 Hz, 945000 pts/s	60°(H)x20°(V)	0.1°(H), 0.16°(V)	2cm
Livox/Mid-40	905nm	1	OPA	260m	100000 pts/s	Circular 38.4°	0.05°	2cm
Livox/Avia	905nm	1	OPA	450m	240000pts/s	70.4°x77.2°circular	< 0.05°	2cm
Hokuyo/UXM-30LN-PW	905nm	1	Rotation motor	30m	50 msec	190°(H)	0.25°(H)	50mm
Intel RealSense/L515	860nm	1	MEMS mirror	9m	30 frame, 23000000pts/s	70°(H)x55°(V)	1024x768 pixels	14mm
Quanergy/S3-2NSI-S00	905nm	na	OPA	20m	25Hz	50°(H)–4°(V)	0.1-1°	na
Leishen/LS21F	1550nm	na	MEMS	250m @%5	30 Hz/4Mpts/s	60°(H)x25°(V)	0.15°(H), 0.1°(V)	5cm

3.3 Multi-Beam LiDAR

The multi-channel (beam) LiDAR data consist of several single channel LiDAR data. A comparison with the single-channel LiDAR data, the channel dimension information is added to the multi-channel LiDAR data. Multi-channel LiDAR data have a large amount of data and a complex structure, and the storage methods of single-channel LiDAR systems are not applicable to multi-channel LiDAR data. MBL data storage is usually solved with the tree structure method (Chen et al., 2022). The measurement is made with multi beams in a 2D plane. Multiple beams are emitted simultaneously, and one or multiple returns are recorded. The channels consist of a line array receiver to record the reflected signals (Fig. 2). Every channel data needs filtering and outlier removal. To combine the multi-channel LiDAR data, a coarse-to-fine registration strategy which combines the normal distribution transform (NDT) algorithm with the iterative closest point (ICP) algorithm is offered (Li et al., 2022).

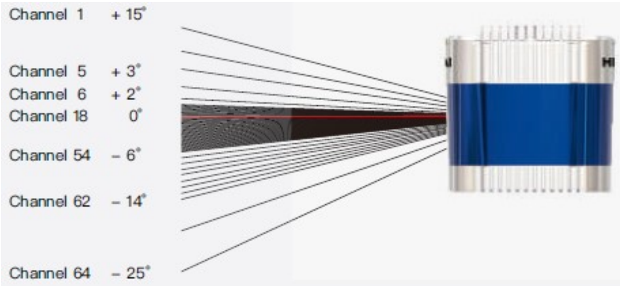

Figure 2. MBL channel distribution (Hesaitech, 2021)

The distribution of LiDAR beams throughout the scene is released by a spinning mirror. The mirrors may spin in a rotating way until 360 degree angle to channel plane deflection. These spinning devices have moving mechanical parts, and thus affect the quality of the measured point cloud. A calibration is continuously required, leading to higher surveying costs. These scanners have a compact structure with a few moving parts and their energy consumption is low. They are widely used for mobile mapping and root detection of mobile robots (Fig. 3). It is also used in guiding and mobile mapping of unmanned ground vehicles (UGV). Their main factor influencing productivity is the number of laser beams emitted simultaneously; and the maximum number of beams is 128, currently (Table 3). The MBL is also called Hybrid LiDAR and has properties of solid-state LiDAR camera (McManamon et al., 2017) and line scanners.

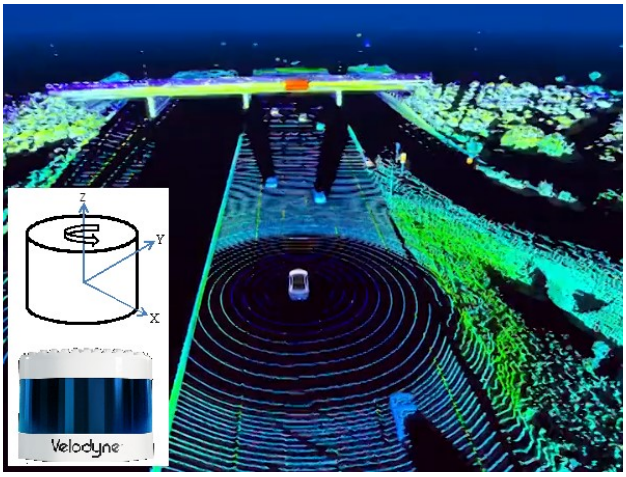

Figure 3. MBL coordinate axis and measurement data (partly adopted from *velodynelidar*)

Table 3. Technical specifications of multi-beam LiDAR.

Company/ Product	Laser wavelen gth	Channel	Range	Scanning rate	FoV (HxV)	Angular resolution	Range accuracy	Energy consumpti on	Retur n puls
Velodyne/ HDL-32E	903nm	32	100m	695000pts/s	360°,40°		2cm	na	na
Ouster/OS 2-128	865nm	128	240m	20Hz, 2621440 pts/s	360°,22.5°	0.18°(H),0. 18°(V)	2.5-8cm	20W	na
HESAI/Pa ndar 64	905nm	64	200m@%1 0	20 Hz	360°,40°	0.4°(H),0.1 67°(V)	2cm	22W	2
Quanergy/ M8-Ultra	905nm	8	200m@%8 0	20 Hz, 1.3M pts/s	360°,20°	0.03-0.13°	3cm	18W	3
LSLiDAR/ C32	905nm	32	150m	20 Hz	360°,31°	0.36°(H),0. 33°(V)	3cm	9W	1
LSLiDAR/ CH32	905nm	32	200m@%2 0	20 Hz	120°,22.25°	0.18°(H),0. 81°(V)	2cm	10W	1
LSLiDAR/ HS8	905nm	8	100m@%1 0	160Hz	120°,9.32°	0.18°(H),1. 33°(V)	2cm		na
LSLiDAR/ MS03	1550nm	4	2000m	60 Hz	120°,9.32°	0.007°	2cm	14W	3

Table 4. The specifications of multi-layer LiDAR instruments.

Company/ Product	FoV (HxV)	Range	Spot size	Scanning rate	Angular resolution	Light source	Return pulse	Scan planes	Energy consumption
SICK/MR S1000	275x7.5	30m@%90	10.4mradx 8.7mrad	4x12.5Hz	0.25°	850nm	3	4	30W
SICK/MR S6000	275x15	75m@%90		10Hz	0.13° (H), 0.625° (V)	870nm	4	24	20W

Table 5. The specifications of rotating 2D LiDAR instruments.

Company/Pro duct	Scanning angle	Range	Scanning rate	Azimuthal Angular resolution	Light source	Amount of evaluated echoes	Range accuracy	Energy consumption
Acuity Tech./ AL-500	360°(H)x12 0°(V)	300m@30 reflectance	200000 pts/s	0.157mrad	905 nm	4 returns	8 mm@ 20m	na
Acuity Tech./ AL-500AIR	360°(H)x12 0°(V)	300m@%30 reflectance	200000 pts/s	400 µrad	905 nm	4 returns	8 mm@ 20m	6W

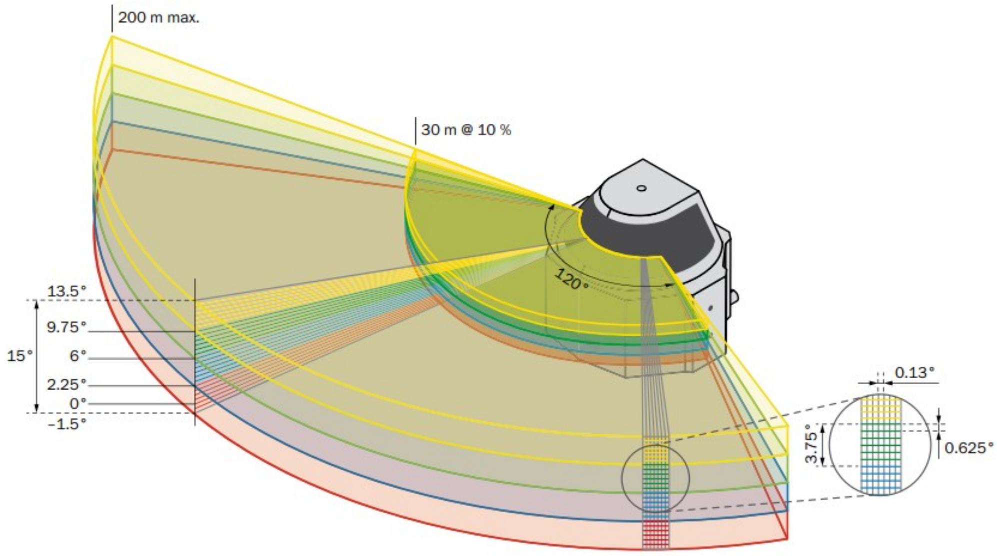

Figure 4. Operational diagram of MRS6000 multi-layer LiDAR. Each polygon mirror is used to tilt one sender output of 6 beams. Thus, a complete rotation of the polygon with 4 polygon sides and 24 planes is achieved (Weber, 2018).

3.4 Multi-Layer LiDAR

By using multiple emitters and receivers, or a combination of both, MLL can be produced with the capacity to scan multiple planes simultaneously or at offset angles (Fig. 4). This means that the sensors of device generation, in addition to the horizontal 2D plane (which is the 0° plane in a horizontally positioned sensor), can scan further planes tilted up or down (Weber, 2018). 3D LiDAR data is obtained from multiple emitter and receiver systems placed at different horizontal angles of a sensor scan while moving. This is now known as a multi-layer scanner. The scanner records distance, angle at the horizontal level, and angle at the different levels of the three-dimensional space of the scan points. Using these three spatial data, the position of a measured point can be determined in the instrument reference frame as XYZ coordinates.

Multi-layer systems are available in a range of different designs. In the MRS1000, the internal emitter and receiver modules are designed to achieve tilted planes. The MRS6000 uses a polygon mirror to reflect the light. The mirror allocates multiple emitters one over the other (Table 4). This is an alternative principle used to generate more measuring levels with a single scanner. A polygon mirror is used to tilt one emitter output of 6 beams, thus achieving a complete rotation of the polygon with 4 polygon sides and 24 planes. The multi-layer LiDAR offers gap-free scanning of the entire horizontal aperture angle (Weber, 2018). Featuring multi-return evaluation capability, the sensor can take measurements over long ranges and produces low levels of noise in the measurement data. A multi-layer scanner also makes fast point cloud acquisition.

3.5 Rotating 2D LiDAR

This type of laser scanner rotates 360 degrees perpendicular to a 2D LiDAR plane to scan the environment (Fig. 5). The rotation makes it possible to capture 3D scan data. The scanning may be continuous or delimited by present azimuth start and stop angles (Table 5). They can be used on stationary or mobile platforms. The number of lines acquired in a scan and the line spacing and slope is determined by the predefined parameters, which are azimuth start and stop points and the azimuth and scan line speeds. They are proper for vehicle navigation, obstacle detection, forest investigation and airborne mapping.

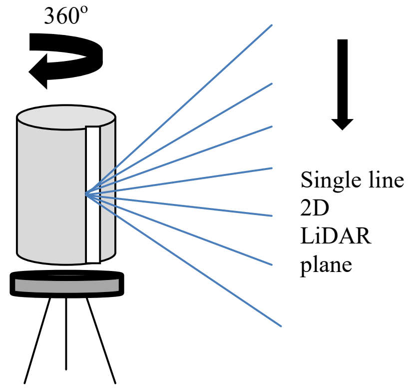

Figure 5. Schematic diagram of rotating 2D LiDAR. 2D LiDAR plane perpendicular to 360 degree rotation axis.

4. DISCUSSION

The advanced LiDAR techniques increased the use of laser scanners for 3D survey and robotic applications. The high measurement speed and accuracy provided by LiDAR technology are effective in this. LiDAR measurements can be applied from static or moving platforms. With the reduction in laser scanner sensor dimensions and weight, scanning with UAV and terrestrial backpack mobile devices has become widespread. In this way, indoor, rural and urban areas that cannot be reached by vehicles can be viewed. In addition to laser scanners, GPS, IMU and other sensors are integrated into mobile surveying. A wider FoV combined with a longer scanning range, high output rate of points and better range accuracy will always be of significant importance when selecting the most suitable LiDAR device for a mobile mapping system (Alsadik, 2020a).

LiDAR is an active measurement technique applied in the day or night time. The measurement accuracy highly depends on the measuring distance and the intensity of the reflected beam. MBL is particularly common in autonomous vehicle navigation, robotic application and mobile mapping. The widespread use of these MBL causes interference effects between the sensors during the record of the reflected beams. The interference effect is prevented by advanced software in some devices. The laser scanners are a whole with the software they provide. The detection and evaluation of multi-return signals, as well as elimination of interference effects, is possible thanks to laser scanner software. A possible effective usage of different types of laser scanners is given in Table 6.

Table 6. A possible application area for laser scanning techniques.

Scanning technique	Possible application area
Mechanical scanners	Object and building 3D modelling, topographic measurement
MEMS	Ideal for sidewalks, commercial and industrial settings. Autonomous and robotic applications
OPA	Security, industrial automation, transportation, and mapping
MBL	Autonomous vehicle, mobile terrestrial mapping, aerial 3D mapping, and security surveillance, smart city applications
MLL	Port management, mining, traffic, security, surveillance counting
Rotating 2D LiDAR	Autonomous vehicles, industrial use, 3D scene capture, drone and air vehicle airborne mapping

3D LiDAR measurement enables to getting high density spatial data for 3D visualization and spatial analysis. In addition, many smart city applications, that are hot topic for researcher, use 3D data to perform many tasks such as security, human mobility, municipal decisions and etc. More analysis is possible from point cloud data with segmentation and classifications.

5. CONCLUSION

It is clear that the scientific developments will generate new techniques that will provide higher speed and accuracy in LiDAR measurement. An efficient usage of laser scanners is possible by knowing their technical specifications and capacities. In the case of possible vibration and impact of laser scanners with moving parts, their internal calibration may be impaired and measurement errors will occur. This is a problem encounter especially in mobile equipment. Thus, compact scanners with fewer moving parts are used in mobile surveying. The adjustable point density, high accuracy, and high speed acquisition make favour the laser scanners for the 3D point cloud acquisition task. Laser scanners are widely preferred for point cloud measurement due to the convenience they provide. 3D point cloud is an indispensable data source for virtual reality, robotic applications, smart city applications, etc.

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