Lidar Technology

Yufeng Hou and Zuoming Zhao

Abstract In the 2005 DARPA Grand Challenge, Stanford's Stanley robot car, navigated by 5 roof-mounted SICK Lidars, won the race against 4 other competitors. Since then, Lidars have gradually become crucial perception sensors for autonomous driving and ADAS, due to their ability to generate real-time point clouds with accurate 3D information of the vehicle's surroundings. Extensive research efforts have been invested into Lidar technology in both academia and the industry. As a result, a diverse variety of Lidar sensors have been created in the past decade. In this chapter, the authors aim to review the state of the art of Lidar sensors for autonomous driving or ADAS applications. The manuscript discusses the important metrics for Lidar sensor performance: detection range, field of view (FOV), angular resolution, frame rate, and eye safety. Then, different Lidar mapping methods and distance calculation mechanisms are discussed. Current status of mechanical, MEMS, FLASH, optical phased array (OPA), and frequency-modulated continuous wave (FMCW) Lidars is introduced, and their pros and cons and reliability performance are compared.

1 Introduction

Light detection and ranging (Lidar) provides the 3D depth information by sending out the laser pulse and measuring the pulse reflected back from objects. Since the first demonstration of Stanford's Stanley with 5 roof-mounted Lidars during DARPA's Grand Challenge, the Lidar has been a critical component for autonomous driving. All the following Grand Challenges proved the necessity of Lidar for autonomous navigation. All major players targeting Level 4 and above autonomous driving technology have equipped Lidars to get reliable 3D information from the surroundings. Multiple companies have successfully developed the Lidar for the autonomous driving market.

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There are Lidars to cover the different distance ranges up to 250 m for autonomous systems.

Short-range Lidar covers the range up to 50 m or shorter. It normally works with a near field camera to detect and track objects nearby, like pedestrians, cyclists, and blind spots. It provides extra safety detection where cameras have difficulty to determine the distance.

Long-range Lidar covers the range from 50 m to a few hundred meters. Sometimes, the range between 50 and 100 m is also called medium range. The Lidar in this range is critical for an autonomous vehicle to be able to operate in high-speed freeway condition.

2 Overview of Current Lidar Technology for Automotive Application

Lidar has been used in autonomous driving vehicles by many companies, like Waymo, Argo, Cruise, and Aurora. It has been proved to provide additional spatial information for the surrounding driving environment. Since the first demonstration of autonomous driving with Lidar, many types of Lidar have been developed. These Lidars with different designs and principles will be discussed in the following sections of this chapter. For the automotive applications, Lidar provides 3D depth information to the autonomous driving system. It helps the autonomous driving system accurately identify the objects, track movement, and make accurate decisions for actions. In order to cover an all 360° view from a few meters to a several hundred meters distance, the Lidars for different ranges require different designs of optics, detectors, and lasers. Therefore, multiple Lidars are required for detection in short, medium, and long range.

3 Important Performance Metrics for Lidar

A Lidar needs many components to be able to generate 3D depth images. A transceiver, a beam steering device, and data processing ICs are the main building blocks. A transceiver has two key components, a receiver (Rx) and a transmitter (Tx). A transmitter generates the light pulse. It includes a laser or laser array, optics to configurate the beam, and electronics to drive the laser device. A receiver detects the photon that is reflected back from targets. It includes a photodetector, readout circuits, and optics to improve the detection efficiency. A beam steering device is used to steer the laser beam to form an image up to a 360° surrounding view. Data processing ICs process the data instantaneously to get the 3D information and transfer this information to the autonomous driving system to perform its next actions. Figure 1 shows a schematic transceiver beam getting sent to the target and reflected back from the

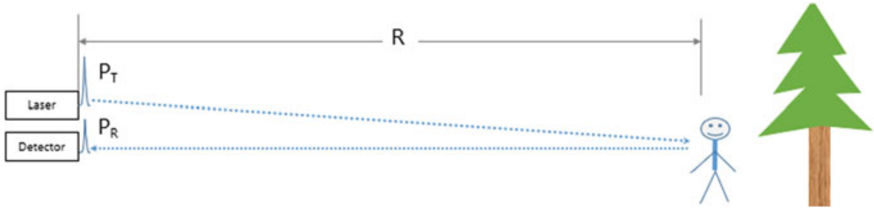

Fig. 1 Schematics of lidar detection

target. The light detected by the receiver can be expressed by Eq. 1, shown below [1].

$$P_R = P_T \frac{\sigma}{A_T} \frac{A_R}{\pi R^2} \eta_{\mathrm{atm}}^2 \eta_{\mathrm{sys}} \tag{1}$$

where P_R is the power received by the receiver, P_T is the transmission from the transmitter, σ is the cross section of the Lidar, A_T is the illumination area of the transmitter, A_R is the receiver area, R is the range between the Lidar and its target, η_{atm} is the transmission efficiency of the atmosphere, and η_{sys} is the transmission efficiency of the Lidar optical system. From this equation, we can conclude that the key figures of merit for the Lidar performance are range, FOV, laser power, receiver sensitivity, and angular resolution. Safety will be another factor that limits the operation of Lidar since it will limit the highest laser power that can be emitted to the target. This will also eventually limit the maximum range of a Lidar.

3.1 Range

With laser power capped by eye safety limitations, the range for a time-of-flight Lidar will be limited to the number of photons that can be detected by the receiver over the total noise. Based on Eq. 1, it can be concluded that the range will be related to the attenuation of the air, the optical efficiency of the system, and the sensitivity of the photodetector in the receiver for a given reflectance of a target. Lasers with a wavelength of from 800 to 1550 nm are used in most commercial Lidar applications. The eye safety limit varies with wavelength; the longer the wavelength, the higher the limit. Semiconductor lasers in this wavelength range are mostly III–V lasers. The photodetector is normally based on an avalanche photodetector (APD) due to its large gain. A silicon APD has a lot of advantages including its cost, integration, and process maturity. However, due to its indirect band-gap structure and 1.1 eV bandgap, it only provides reasonable sensitivity for wavelengths shorter than 1 um. For any wavelength beyond 1 um, a III–V APD will be required for good quantum efficiency.

With limited laser power and detector capability, the detector range will be strongly affected by the detector's optical design and atmosphere absorption. The solar spectrum through the atmosphere and extraterrestrial space from the American Society for Testing and Materials [2] is shown in Fig. 2. Several minimum absorption dips can be used to optimize the absorption loss. However, there will be a balance between absorption and background noise. Minimum absorption normally corresponds to a large background solar spectrum. For example, 940 nm has minimum background noise but it also has the highest absorption by water molecules. As shown in Fig. 2, there are significant advantages to using a short-wavelength IR where the solar background and absorption can be optimized. The band around 1400 nm is especially interesting because there is a wide area to optimize the absorption and background noise to achieve a large detection range. An extra advantage for the band around 1400 nm is the high cap on laser safety which will be discussed in a later section. On the other hand, the band around 940 nm has very mature III-V laser and Si-based photodetectors, which will give a big advantage for cost but less range. Currently, the commercially available Lidars which are using Si-based detectors only provide a good detector range up to 100 m with the reflectance around 10%. The long range beyond 100 m will need to be explored using the 1400 nm band.

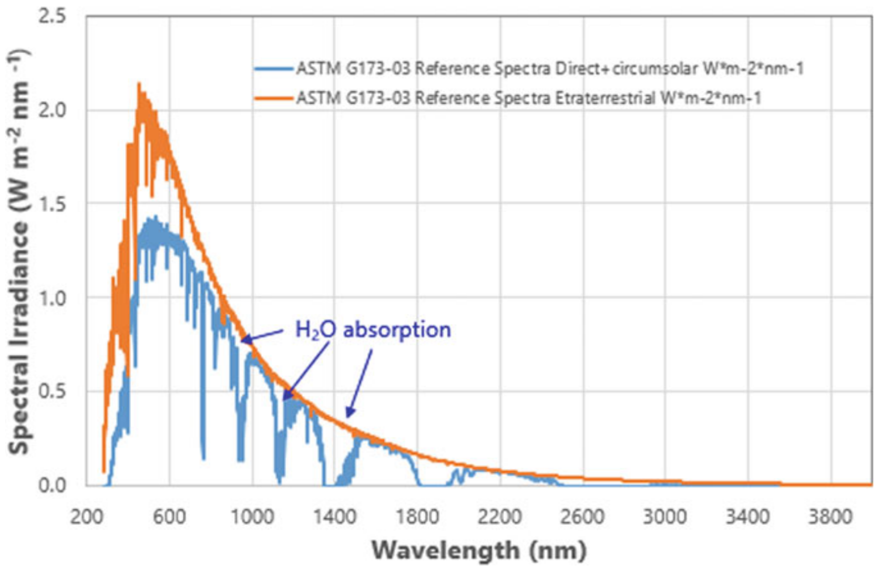

Fig. 2 Spectral irradiance from solar through atmosphere and extraterrestrial

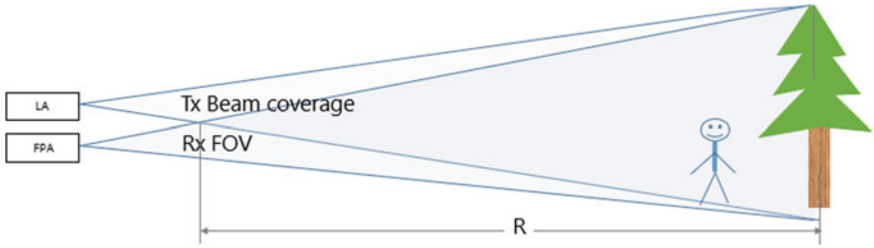

Fig. 3 Rx field of view and Tx beam coverage

3.2 Field of View

The field of view describes the maximum angle that can be viewed by a focal plane array (FPA). The larger the FOV, the wider the field the FPA can see. For an autonomous driving Lidar system, a larger FOV will give the detector larger detection areas to detect more objects. However, a larger FOV will also require larger beam lines to the field and a higher total laser power. As Fig. 3 illustrates, Lidar detects the points where a laser beam shines on. The Lidar can only detect the effective range *R* where there is sufficient overlap between the laser beam and the FPA FOV. The upper limit of range *R* will be limited by the signal-to-noise ratio of the system.

As the FOV increases, the beam coverage will also need to increase. The beam energy is quickly spread in the fast access direction. The photon reflected back to the detector will also quickly decrease. This will bring more challenges for FPA to have sufficient signal to maintain a good probability of detection on target. The large FOV will eventually eat in the margin on the maximum detection range. Therefore, it needs to balance on the range performance and FOV.

3.3 Angular Resolution/Accuracy

Angular resolution of Lidar is the smallest object that the Lidar can differentiate in angular direction where a beam is steered. It determines the capability of the Lidar to detect small objects in an angular direction. It will be reflected in the density of data points in a point cloud. Figure 4 shows the top view of the Lidar beam projection on an object. If the beam scan is between points 1 and 4, the higher the angular resolution, the more data points measured from the object. It will provide more information to the AV to detect and track an object.

The factors which determine the angular resolution are the detector sensitivity, beam steering accuracy, beam size, and FPA frame rate. The high detector sensitivity can provide advantages of small beam size and quick integration to detect the target. An accurate beam steering system will give better position accuracy in the angular direction. The small beam size will reduce the overlap between the lines and give a

Fig. 4 Angular resolution of lidar

detector better signal-to-noise ratio. Finally, the fast frame rate is needed to process the data between angular lines. This requires the detector to have a sharp rise time and short duration after pulse to be able to differentiate each return pulse from targets.

3.4 Frame Rate

The Lidar frame rate is different from the detector frame rate. Lidar frame rate refers to the point cloud frame rate. That is determined by the beam steering frequency. These two rates will affect each other. The faster detector frame rate will give more room for Lidar frame rate which affects the point cloud quality.

The detector frame rate is the data processing speed of the FPA. It limits the Lidar's capability to detect moving objects. A high detector frame rate will allow Lidar to detect high-speed moving objects. The detector frame rate is mainly determined by the detector speed. For most APD, the ranging gate setting and readout IC time bin setting define the data process readout speed. Intrinsically, it is how fast the FPA can be armed.

The Lidar frame rate is the frame frequency of the full view of the point cloud. The beam steering system will limit the frame rate. The mechanical steering system will have a very limited frame rate around 10 Hz. Other advanced beam steering systems which will be discussed in the later sections can provide high frame rate.

3.5 Eye Safety

Eye safety defines the maximum laser exposure dose that is safe for the human eye. It uses maximum permissible exposure (MPE) to define the highest energy density of lasers that is still safe for the eye. It is usually about 10% of the dose that has a 50% chance of causing damage under worst-case conditions. The infrared light with a wavelength longer than 1400 nm is absorbed by the transparent parts of the eyes before it reaches the retina. This is the reason why there are orders of magnitude of more margin for eye safety when using long-wavelength lasers around the range of 1500 nm. Figure 5 shows the MPE at different wavelengths. From 1000 nm, there is a significant margin increase for longer wavelengths up to 1500 nm. However, the cost of the device will increase significantly due to the expensive III-V manufacturing process compared to Si process which can only work below 1000 nm.

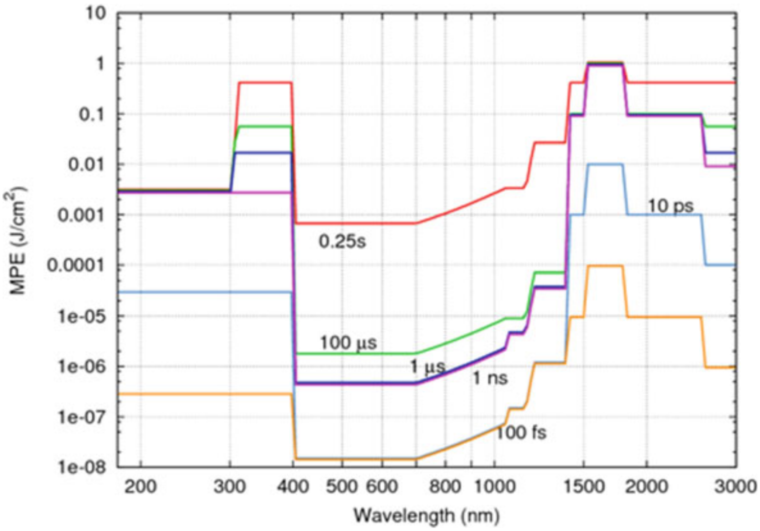

Fig. 5 MPE limit for different wavelengths [3]

4 Transmitter and Receiver

A transceiver is the module that generates the point cloud data in a Lidar. It has 3 main parts—a transmitter (Tx), a receiver (Rx), and the data process electronics. Tx is the module that emits the light pulse, and Rx is the module that detects the pulse. Lidars for autonomous driving are mostly based on semiconductors. Both photodetector arrays and laser arrays are semiconductor-based devices due to their small form factor and easy integration to data process electronics. Data process electronics are application-specific IC, FPGA, or SOC integrated with other voltage regulators or sensors on a PCB board. With different working wavelengths, the device design of semiconductors will be significantly different. Table 1 summarizes the pros and cons for different IR wavelengths. IR with Si-based Rx has a significant advantage on cost, while short-wavelength IR (SWIR) with III-V based Rx provides a large detection range which is crucial for long-range detection to enable the high-speed operation due to higher photon detection sensitivity in short-wavelength IR range.

5 Distance Calculation

The distance calculation of an AV Lidar is mostly based on the time-of-flight principle or phase shift of the light pulse. As Sect. 3 has discussed most of the figures of merit, this section will focus on distance calculation.

Table 1 The comparison for lidar applications between IR <1000 nm and SWIR >1000 nm

Metrics	IR <1000 nm	SWIR >1000 nm
Materials for Rx	Si-based Rx	III–V based Rx
Materials for Tx	GaAs-based Tx	InP-based Tx
Control/readout IC integration	Easy integration Rx with digital IC	Poor integration with digital IC
Cost of materials and process	Low cost for both Rx and Tx	High cost for both Rx and Tx
Reliability	Good reliability	Poor reliability
Manufacturing capability	Well established manufacture capability	More process development required
Development maturity	Good understanding with main failure modes	Limited research in reliability and degradation
Detector sensitivity	Low detector sensitivity for IR	High photon detection sensitivity
Detection range	Short detection range	Long detection range
Margin on eye safety	Low margin with small intensity limit	High margin with high intensity limit

5.1 Range of Time of Flight

For a time-of-flight sensor, the range distance can be expressed by Eq. 2, where R is the range distance for time of flight and t is the time for the light to reach the target and reflect back. The range is 15 cm per ns, and the accuracy of the range depends on the pulse shape.

$$R = t \times \frac{c}{2} \approx 15t \tag{2}$$

For the design to detect the edge of the pulse, the rise time of the pulse will strongly affect the uncertainty of the measurement. For the peak detection, the peak width will affect the accuracy. Current semiconductor lasers can achieve ~1 ns width pulse. The range accuracy can be within ~15 cm. However, the target reflectance will strongly modulate the peak shape. This will impact the uncertainty of detection due to the loss of signal-to-noise ratio (SNR) from transmission. Reflectance will also introduce range walk, which needs to be calibrated to avoid extra errors in range detection. The range walk is a systematic range error due to the pulse intensity change.

In order to accurately detect the target which is moving, there are two factors that need to be considered. One is the error introduced from the beam steering system. Another one is from target movement. The time of flight to a 250 m target is only 17 ns from Eq. 2. For a mechanical steering system with 10 Hz spinning rate, the error from the movement to the 250 m target can be calculated from Fig. 4 to be a quarter of millimeter. That is negligible. The movement target with speed of 120 mile/hr will only move around ~1 um. The error introduced by the movement of

Lidar is in the same order of magnitude of the target. This indicates that the effect due to beam steering, Lidar movement, and target movement will not introduce any significant impact on angular resolution.

5.2 Signal-To-Noise Ratio

As discussed previously in Sect. 3 Eq. 1, the detector needs to have enough power from the signal light to be reflected back from the target. The probability of detection will be determined by the signal-to-noise ratio (SNR). The signal is determined by the laser power, reflectance of target, and loss during transmission. The noise sources include detector noise, readout IC noise, or solar background noise. This can be expressed in Eq. 3, shown below.

$$\mathrm{SNR} = \frac{S}{N} \tag{3}$$

In Eq. 3, S is the signal power and N is the noise power. For a popular avalanche detector, the signal will be the photocurrent signal, which is directly related to the detector gain and responsivity for a given input light intensity. Noise can be from either external background or detection optics and electronics.

5.3 Factors that Affect Range Detection

In AV applications, the use conditions will affect the SNR of the Lidar. This will affect the probability of detection on the target. Weather conditions also have to be considered for Lidar development to ensure the device can remain functional in many corner cases, like rain, fog, hail, sandstorm, etc. Rain and fog will strongly scatter the light and reduce the SNR. For different systems, the scattering will be significantly different. The scattering from water drops, molecules, or other particles is inversely proportional to the fourth power of the wavelength and the range. It can be explained by Rayleigh scattering and Mie scattering in Eq. 4.

$$I = I_0 \frac{\left(1 + cos^2\theta\right)}{2R^2} \left(\frac{4\pi^2}{\lambda^4}\right) \left(\frac{n^2 - 1}{n^2 + 2}\right)^2 \left(\frac{D}{2}\right)^6 \tag{4}$$

where I_0 is the light intensity before the interaction with the particle, R is the range distance between the particle and the observer, θ is the scattering angle, λ is the wavelength of light under consideration, n is the refractive index of the particle, and D is the diameter of the particle. The range detection capability will quickly decrease with the density of the raindrops. Short-wavelength Lidar will be impacted more significantly than long-wavelength ones. For very large particles, the direct reflection will take over and Lidar will lose visibility to the objects.

6 Future Direction of Lidar Developments

Although time of flight (ToF) is the current mainstream distance measurement method Lidars are using, new techniques such as frequency-modulated continuous wave (FMCW) are under development and have started to demonstrate advantages in some aspects compared to ToF [4].

6.1 Frequency-Modulated Continuous Wave (FMCW)

In a frequency-modulated continuous wave (FMCW) Lidar, the laser frequency emitted from the laser source, usually a diode to enable coherent detection [5], is modulated by a waveform generator to be varying periodically [6]. As indicated in Fig. 6, a beam splitter splits the transmitted laser into two parts. One part is projected onto the target and reflected back, while the other part goes directly to the mixer as a beat frequency and acts as a reference of the original laser in comparison with the first branch of the emitted wave. It will mix with the other branch of the emitted wave and create a beat frequency [7].

This beat frequency is proportional to the target distance [8–11]

$$f_b = \frac{4BRf_m}{c} \tag{5}$$

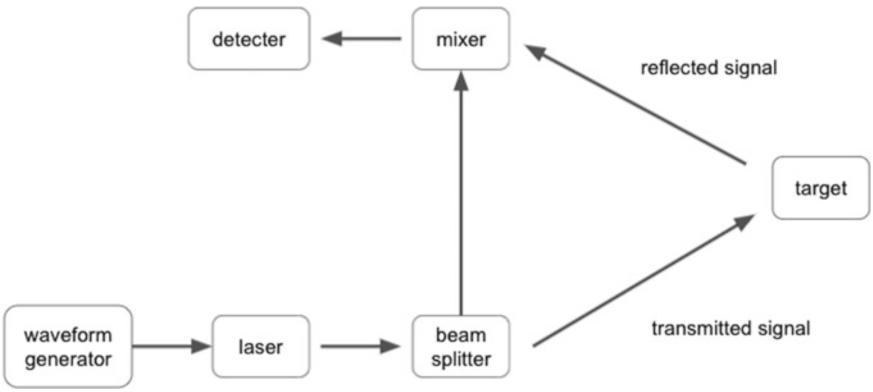

Fig. 6 Simplified FMCW lidar working principle

Here, f_b is the beat frequency, B is the bandwidth of the frequency sweep, R is the target distance, and f_m is the modulation frequency (of a triangular frequency modulation).

One advantage of the FMCW Lidar is that it has the capability of measuring not only the target's distance, but also the target longitudinal velocity and its direction. The velocity contributes an additional Doppler frequency f_d to the beat frequency f_b [12]:

$$f^{+} = f_b + f_d \tag{6}$$

$$f^{-} = f_b - f_d \tag{7}$$

The target's distance is:

$$R = \frac{c}{8Bf_m}\left(f^{+} + f^{-}\right) \tag{8}$$

The target's longitudinal velocity is:

$$v1 = \frac{\lambda}{4}\left(f^{+} - f^{-}\right) \tag{9}$$

FMCW Lidar uses a continuous light source instead of a pulsed laser. This theoretically avoids any blind spots in the object detection. Its capability to measure distance and longitudinal velocity at the same time is an advantage over the ToF method. Since FMCW uses the interference of emitted/reflected laser to measure, it is less likely to be affected by ambient light, such as sunlight or other Lidars.

An incomplete list of developers of FMCW Lidars includes Aeva, Analog Photonics, Argo AI (Princeton Lightwave), Aurora (Blackmore), Baraja, Insight Lidar, OURS Technology, Psionic, SiLC, and Waymo.

7 Mapping Methods

In the last section, two different methods for single-point distance measurement used by Lidar were discussed (time-of-flight, ToF, and FMCW, amplitude modulated continuous wave, or AMCW, is not covered in this chapter). With single-point distance measurement achieved, the next step is to project this laser pointer around in the form of a 3D point cloud covering the 360° surrounding environment of the vehicle. Different methods have been applied to achieve this [4–15] including mechanical scanning, MEMS [16], optical phased array [15], et al. They each have their own characteristics and limitations and will be discussed one by one in detail in this section.

7.1 Mechanical Spinning Scanner

Mechanical spinning scanner Lidars are the most widely applied and most mature Lidar in the market today. It is also technically the most mature scanning mechanism. Multiple sets of laser sources and detectors are aligned in the vertical direction and mounted onto a driving motor. With the driving motor spinning 360° in the horizontal direction, every source-detector also scans a full circle and forms a line of multiple points. All these lines stack up and form a 3D point cloud, as shown in Fig. 7.

Mechanical spinning scanner Lidars usually use pulsed lasers as their light sources. In azimuth direction, their angular resolution is determined by laser pulse spacing, which is usually pretty high (0.08°) [11]. In the vertical direction, their angular resolution is determined by the number of source-detector pairs they have and is usually lower compared with that in azimuth direction. The frame rate is determined by the spinning speed of the driving motor and is usually pretty low, between 1 and 100 Hz [17].

The advantages of the mechanical spinning scanner Lidars include their technical maturity. With hundreds of autonomous testing vehicles on the road for years, they have accumulated the most experience and field mileage. They are still the choice of the majority of autonomous driving companies and their testing fleet for road use and data collection. Most of the data that have been collected and used for training and optimizing the algorithm are generated by mechanical spinning scanner Lidars. They usually have a wide 360° horizontal field of view (FOV) while other types of Lidar usually have smaller than 120° horizontal fields of view as comparison. They also have a pretty far detection range, and the uniformity of the point cloud is usually better than other types of Lidar.

Because of the high structural complexity of the multiple laser-detector pairs, a disadvantage is that mechanically spinning scanner Lidars with high line count are usually very bulky and expensive. Due to the large inertia of the rotating module, their power consumption is usually also very high (Velodyne HDL-64E consumes

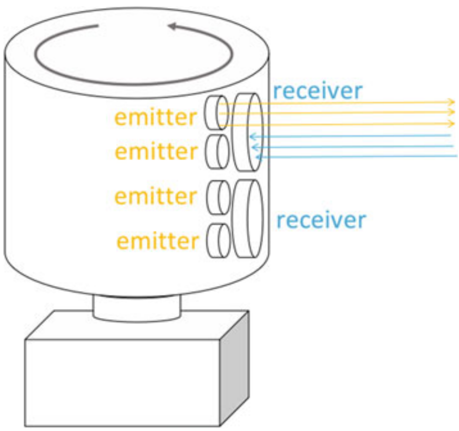

Fig. 7 Simplified mechanical spinning scanner working principle

60 W) [11]. Their reliability and maintenance are also challenging. Under common driving conditions, mechanical vibrations and shocks can easily cause issues such as misalignment and fatigue.

To provide power and transmit data to/from the rotating source-detector modules, slip ring and brush are applied. Issues such as wear out and intermittent connection become common failure modes, limiting the lifetime of the mechanical spinning scanner Lidars to around two or three years. Due to the small installation base and road mileage, and the confidential R&D nature of the self-driving technology, photos showing different Lidar failure modes and FA reports on the root cause are extremely rare on the Internet. The authors will not discuss them in this chapter.

Suppliers for the mechanical spinning scanner Lidars include Velodyne, Hesai, and RoboSense.

Below, we listed some of the mechanical scanner Lidars currently on the market and their specs [18, 19].

Lidar	HDL-64E	Alpha prime	OS2 long-range lidar	Pandar 128	RS-Ruby
Company	Velodyne lidar	Velodyne lidar	Ouster	HESAI	RoboSense
Core technology	Mechanical	Mechanical	Mechanical	Mechanical	Mechanical
Max range	120	245	240	200	250
FOV (horizontal)	360°	360°	360°	360°	360°
FOV (vertical)	26.9°	40°	22.5°	16°	40°
Angular resolution (horizontal)	0.35° (20 Hz)	0.4° (20 Hz)	0.02°	0.1°	0.4° (20 Hz)
Angular resolution (vertical)	0.4°	0.11°	0.01°	0.125°	0.1°
Scan rate	~1.3 M pps (single) ~2.2 M pps (dual)	~2.4 M pps (single) ~4.8 M pps (dual)	~0.6 M pps (single) ~2.6 M pps (dual)	~3.4 M pps (single) ~6.9 M pps (dual)	~2.3 M pps (single) ~4.6 M pps (dual)

7.2 Opto-Mechanical Scanning

Opto-mechanical scanning refers to the usage of optical components, such as mirrors or prisms to steer the laser beam and achieve scanning. To solve the issues of early mechanical spinning scanner Lidars due to their design by integrating laser-detectors on a spinning driving motor, different methods have been used. These include decreasing the number of laser-detector pairs to reduce weight or keeping them stationary and using optical mirrors or lenses to complete the scan. Some examples are using double galvanometer scanning mirrors, gyroscopic mirrors, or Risley prisms for the scanning.

If the optical components only scan in one direction, as in a line scanner, the Lidar still needs multiple laser-detector pairs to cover the whole FOV. Some examples are a slated plain mirror, off-axis parabolic mirror, a polygon mirror, or a single galvanometer scanning mirror.

If the optical components scan simultaneously in 2 directions, only one or several laser-detector pairs are needed to cover the whole FOV.

Examples of the opto-mechanical scanning Lidar include the Scala Lidar installed on the first mass-production L3 level autonomous driving passenger vehicle—Audi A8. The Livox Lidar developed by DJI uses a Risley prism as its scanner.

7.3 MEMS Scanning

Microelectromechanical system (MEMS) mirror Lidar uses a millimeter or centimeter sized mirror to replace motor-driven, macro-scale mirrors or lens. Since there are no motors in the system and limited mechanical parts that will cause friction and wear out, MEMS Lidar greatly reduces the factors that affect the reliability and lifetime of the sensor.

From a cost perspective, every laser-detector pair in a mechanical spinning scanner Lidar costs nearly 200 dollars. A 16-line Lidar's cost is as high as 3200 dollars just for the laser-detectors. MEMS Lidar can greatly reduce the number of laser-detectors needed, thus helping to reduce the hardware cost. Meanwhile, MEMS mirrors can be designed to have wide scan angles and high scan frequencies, which generate dense point clouds and a high frame rate, improving the spatial and time resolution of the mechanical spinning scanner Lidar. The MEMS mirror is fabricated using a mature Si semiconductor foundry process and is largely immune to material fatigue, which is critical for a moving part that needs to tolerate $10^9 \sim 10^{11}$ duty cycles in its lifetime, as shown in Fig. 8.

Based on scan directions, the MEMS Lidar can be categorized into 1D MEMS Lidar and 2D MEMS Lidar.

The major disadvantages of the MEMS Lidar are that although MEMS mirrors are small and immune to fatigue, they are still fast-moving mechanical parts, risking its reliability and precision. This is especially notable in a shock event, which may damage the mirror. Temperature will also affect the material properties in the MEMS mirror and cause drift in scan angle and frequency, which need to be actively compensated.

An incomplete list of suppliers that are developing/manufacturing MEMS Lidars includes Aeva, AEye, Blickfeld, Cepton, Innoviz, Luminar, LeddarTech (Hybrid Flash), Livox, MicroVision, Pioneer, RoboSense, SOS Lab (SL-1), Toshiba, and XAOS.

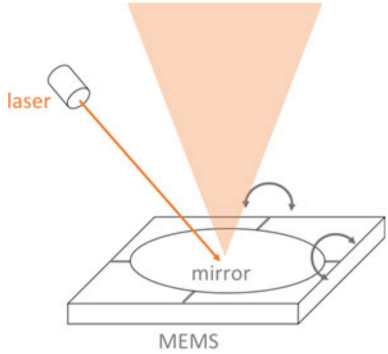

Fig. 8 Simplified MEMS scanning working principle

Among them, Luminar has Iria and Hydra published, and Ira is expected to be in mass production in 2022 and sold at 1000 dollars/unit for L3+ autonomous driving. The first generation of Innoviz Lidar, InnovizOne, has a maximum detection range of 250 m (assume 0.1 reflectivity) and is ordered by BMW. Compared with the previous generation, the latest InnovizTwo's cost has been reduced by 70%.

Below is a list of the MEMS Lidar on the market and their specs [18, 19].

Lidar	4Sight M	InnovizTwo	Dynamic view lidar	Scala2	Vision Mini	RS-LiDAR-M1
Company	AEye (continental)	Innoviz technologies	MicroVision	Valeo	Blickfeld	RoboSense
Core technology	MEMS/ToF	MEMS/ToF	MEMS/ToF	MEMS/ToF	MEMS/ToF	MEMS/ToF
Max range	300	300	250	200	150	200
FOV (horizontal)	60º	125º	100º	133º	120º	120º
FOV (vertical)	30º	40º	25º	10º	50º	25º
Angular resolution (horizontal)	0.1º	0.07º	0.03º	0.125º	0.2º	0.2º
Angular resolution (vertical)	0.1º	0.05º	0.03º	0.6º	0.6º	0.2º
Scan rate	4 M pps	–	10 M pps	0.25 M pps	–	1.5 M pps

7.4 Flash

The name Flash refers to the way the Lidar works similar to the flashlight of a camera when taking a photo. The full field of view is illuminated by a flood laser source,

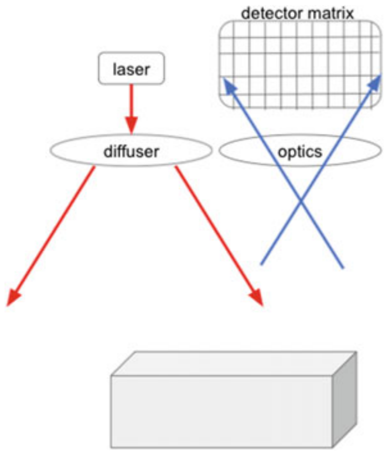

Fig. 9 Simplified flash lidar working principle

usually in a pulse form. An array of photodetectors at the image plane captures the time-of-flight (ToF) signal from every pixel and calculates distance information, which generates a point cloud (Fig. 9).

The advantages of Flash Lidar include the following: (1) A true solid state with no moving parts greatly improves its resistance to vibration and shock. (2) The flood laser source illuminates the entire FOV, which is a more reliable way for object detection compared to scanning certain points in space. (3) Flash Lidar uses an optical lens, which has already matured for years in cameras.

The disadvantage of the Flash Lidar includes the following: (1) Using flood illumination means every pixel in the image is only a small fraction of the returning laser power, which leads to low signal-to-noise ratio (SNR). Low SNR greatly limits the detection range of the Flash Lidar. (2) To compensate for the low SNR, high power laser source is one option; however, the heat management and power will become a problem for a compact Flash Lidar. (3) Low SNR means Flash Lidar is more prone to be affected and cheated by other Lidars from another vehicle. (4) Flash Lidar is relatively new and lacks maturity and experience.

A incomplete list of companies developing Flash Lidars includes Argo AI (Princeton Lightwave), Benewake, Fastree3D, LeddarTech (Pixell), Newsight Imaging, Phantom Intelligence (purchased by LeddarTech in 2020), RoboSense, Sense Photonics, SOS Lab (ML-1), TetraVue, Valeo, and Vergence Automation.

7.5 Optical Phased Array (OPA)

In an optical phased array (OPA) Lidar, the laser power is split into an array of transmitters. The phase of each transmitter can be controlled individually. By tuning the relative phase shift among transmitters, a laser beam can be formed and steered (Fig. 10).

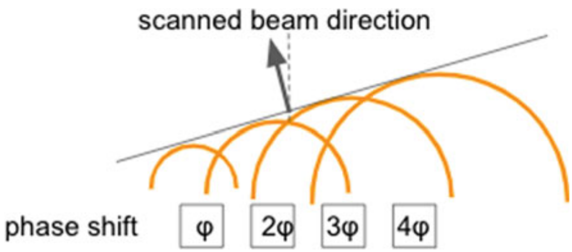

Fig. 10 Simplified OPA Lidar working principle

The advantages of OPA Lidar include the following: (1) There are no moving parts in the Lidar, which ensures good reliability and prevents any extra noise during the operation. (2) OPA Lidars use optical lens, which have already matured for years in cameras.

The disadvantages of this scanning method include the following: (1) In the transmitting and receiving stages, the dissipated light of the laser beam on the side lobes will reduce the efficiency and detection range of the Lidar. For example, the Quanergy S series of OPA Lidar only has an effective detection range of 11 m and currently is applied in low-speed short-range scenarios, such as parking assistance. (2) This concept is rather new and lacks maturity and experience.

An incomplete list of companies developing OPA Lidars includes RoboSense, Quanergy, Analog Photonics, NepTec, Voyant Photonics, and XAOS.

8 Discussion

The pros and cons for different scanning mechanisms of Lidar are summarized in the table below.

Scanning method	Pros	Cons
Mechanical	• Good precision in single-point distance measurement • High resistance to interference • Tolerance to work under high power laser	• Difficulty to meet automotive industry standards • Vertical scan angle fixed, difficulty in assembly and mass production
MEMS	• Highly integrated, compact in volume • Low wear out • Mature Si wafer processing easy for mass production	• Difficulty to control high precision high frequency scan • High wafer fabrication requirements • Limited FOV, cannot achieve 360 degree coverage, needs a combination of multiple units

(continued)

(continued)

Scanning method	Pros	Cons
Flash	• No scan needed • Fast imaging speed • Highly integrated, compact in volume • Mature optical CMOS technique, easy for mass production	• Laser power limitation • Relatively short detection range • More prone to interference and crosstalk • Low angular resolution
OPA	• Fast scanning speed • High scanning precision • High controllability	• Side lobes affect detection range and angular resolution • Complicated, hard to manufacture

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