Lidar Sensor in Autonomous Vehicles

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***Abstract*— Lidar (Light detection and ranging) accounts for the key component for Autonomous driving architecture. It holds the backbone for current AVs (autonomous vehicles) because of two important characteristics object detection and Depth estimation. Due to its high sensitivity and accuracy, it has several applications in robotics, Advanced driver assistance systems, level five autonomous driving and other domains requiring 3D interpretation and visualization of images. Lidar not only adds to comfort domain, but also prevents from severe accidents. Advancements made in lidar sensors and transition from mechanical scanning system to latest FMCW and flash technology are discussed.**

Keywords*— *Lidar, Point cloud, 3d imaging, object detection, depth estimation, Autonomous vehicle, Advanced Driver assistance system

I. Introduction

Lidars are a hot a multibillion industry. Not only can one think of added luxury but autonomous cars can add to the expanded transportation options and an ease of accessibility for the disabled and senior citizens. Moreover, businesses will expand as mobility acquires an essential aspect when talking about trade. An autonomous car means a vehicle or an automobile that can steer itself from one position to another by sensing environmental conditions. A human may select the destination and initial parameters, but he is not required specifically to drive and steer the vehicle. Various sensors are required, which includes Radar, Optical Imaging sensors(Camera) , GPS, Lidar , Ultrasonic Sensor and many others. However, the backbone sensors that constitutes autonomous driving control system includes RADAR which is mounted on both bumpers which provides distant sensing, camera sensor provides visualization of the surrounding and aids in detection of traffic light, traffic signals and other objects on the road. Similarly, Lidar which is based on the principle of lasers is also used for object detection and tracking. Moreover, it is also used for depth estimation and distance finding. The ECU then process these signals from the sensors for decision making. From the results and calculations performed by ECU, actuators are activated which in turn controls the functionality of the vehicle. Fig 1 represents the communication infrastructure of an autonomous vehicle [9].

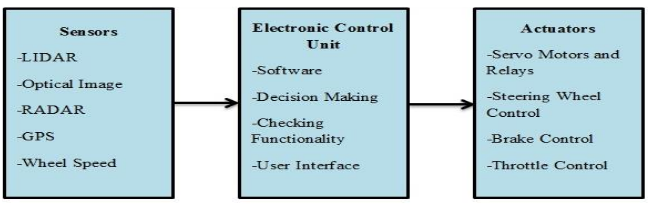

Fig.1. Autonomous vehicle architecture [9]

Practically, different manufacturers often combine lidar with the camera in order to complement each other. Camera is not a good choice for distance estimation while the lidar is the perfect choice for distance calculation. On the other hand, camera is better choice for object recognition [4]. This combination of different sensors give birth to the idea of sensor fusion. Right now, various research and experiments are in progress in the domains of computer vision and deep learning methods to calculate and estimate distance on 2D image data. However, keeping in mind safety and cost saving factor, a redundant approach is necessary which supports the idea of sensor fusion [1].

The exact location estimation is a major ability required by most independent autonomous frameworks. With a localization system, a portable robot or a self-sufficient vehicle is skilled to estimate it's anything but a guide dependent on perceptions with onboard sensors. Exact and solid LiDAR-based global localization is required for independent driving, particularly in GPS-denied conditions or circumstances where GPS cannot provide precise limitation results [6]. For instance: A man took around dozens of mobile phones in a car with driving mode on GPS and GPS considering all cellphones as a driving unit declared the track as impacted by traffic congestion. That is why the idea of using GPS for location estimation may be correct, but it cannot be used for wider purposes.

In the late twentieth century, Lidar which stands for (Light detection and ranging) has depicted tremendous progress. In the past, it was used only for the purpose of aerial mapping and was a part of aviation industry [2]. Around 1.35 million individuals fall prey to street accidents each year; on normal 3,700 individuals lose their lives each day on the streets. An extra 20-50 million endure non-deadly wounds, regularly bringing about major disabilities. The greater part of all street traffic passing happen among weak street clients—people on foot, cyclists, and motorcyclists [10]. As far as the stats depict the importance of safe driving. Consequently, when transitioning from manual driving to autonomous driving, there is an increased demand for driver safety and vehicle stability to prevent accidents and major catastrophe.

The concept of lidar is not new, and it is being used for various purposes for long times. How this idea came into the automotive industry is quite interesting. In 2004 DARPA grand challenge was announced which invited everyone to test their own automotive vehicles. This event was although unsuccessful as 142 miles long race course cannot be completed by any competitor. However, it led to the birth of lidars in automotive industry. The same series of event took place in 2005 with the same name DARPA Challenge. Stanford 's Stanley took part in this competition. Five sick based LMS-291 lidars were mounted on the winning car. However, interestingly Hall brothers participated in the race and could not win. On the other hand, their idea of using 360° spinning lidar gained massive popularity. Eventually, in 2007, five out of 6 winners from Darpa were using the same technology provided by Velodyne lidar [5]. According to a report by BIS Research, the car lidar market is predicted to develop from $353.0 million in 2017 to $8.32 billion by 2028 at a consolidated yearly development pace of 29.6% and reach $44 billion by 2050 [6]. To add with, Intel predicts a 7 trillion economic revenue influx in vehicle industry by 2050 powered by Autonomous Vehicles [5].

II. LIDAR

Lidar (light detection and ranging) with the aid of the laser phenomenon illuminates its vicinity by ejecting lasers. Those transmitted laser pulses are then reflected back. Those reflected pulses from certain obstacles are then detected via a receiver which is generally a photodetector for instance, a Single photon avalanche diode (SPAD) or avalanche photodiode (APD). Distance is measured by simply calculating the reception of the reflected laser pulse with reference to the transmitted pulse. By knowing the position, lidar allows to calculate the 3D points. Compared to other imaging and range measurement techniques such as camera and radar, lidar always has an upper hand in terms of accuracy, reliability and range. Why lidar is a better choice as a standalone vision sensor will further be elaborated in detail. [8] Moreover, lidar also holds key perspective to the future of autonomous driving because of the concept of sensor fusion and redundancy approach. One more important characteristic of lidar is its applications in multiple domains.

- Object Detection
- Object tracking and recognition
- Object mapping and depth imaging

A. *Working Principle*

Lidar sensing works on the principle of laser technology,
It is generally a remote sensing technology and consists of laser light which emits a high beam with definite coherence, focus and chromaticity [7]. The reflected light from the hinderance is sensed by the photodetector also termed as a receiver. The distance is calculated by measuring the time when the pulse was transmitted and received back to the receiver. By using a simple equation of motion and substituting the value of speed of light in the air and total time of flight one can easily calculate the distance of an object from lidar.

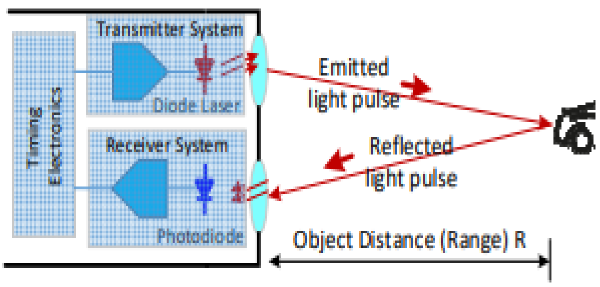

Fig. 2. Lidar operating principle [5]

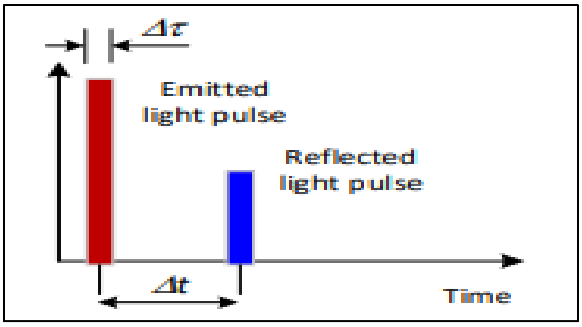

Fig. 3. Lidar pulse timing diagram [5]

$$R = c\Delta t \cdot \frac{1}{2n} \qquad (1)$$

Where,
R = measured range of the lidar sensor
c = speed of light in m/s
n = refractive index of the medium where light propagates
Δt = time gap between transmission and reception of laser

Speed of the light is $3x10^8$ m/s for air (if an index of refraction = 1). Value of refractive index changes for every medium. The greater the value of refractive index the lesser will be the range as per working formula. Table 1 shows different values of the refractive index of common materials. From fig. 3 it is evident that reflected pulse power and amplitude is lesser than the transmitted. It is because the reflected power decrease quadratically with relation to distance. The whole power equation and efficiency is discussed in the lidar power section. Assuming all these parameters and conditions and if we substitute appropriate values in formula, a target which is located at 150m will result in the total time value of 2µs. (total time = transmission + reflection) [5].

TABLE 1. REFRACTIVE INDEX OF COMMON MATERIALS

Material	Refractive Index
Air	1.0003
Water	1.33
Ice	1.31
Alcohol	1.36
Crown Glass	1.52
Diamond	2.42
Rock salt	1.54

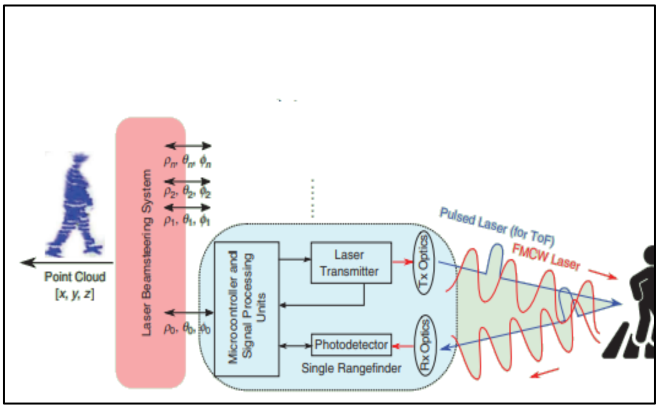

Fig. 4. Point cloud estimation with lidar [4]

Beside range calculation, 3D image formation is also done through this. The lidar generates 3D point clouds that relates to the scanned environment and intensities that are received at the receiver end [4]. Fig 4 shows how using point cloud data image is constructed using a lidar. In this way not only object distance but also its image construction using coordinates is possible. In this figure 4, a laser emitting from a source is transmitted. When a laser is blocked by an obstacle, it bounces back and is received at the receiver. The receiver photodetector then transfers the data to microcontroller or processing unit for calculation. Through calculation, it processes and yields 3D points in the spherical coordinates system to the laser beam steering section. The point clouds are then collected and an image of the resultant object is formed through point clouds. There are 3 coordinate systems namely spherical, cylindrical and rectangular. We are using spherical coordinate system in this case because of certain criteria. Generally, lidar calculates the points in spherical system because two angles are being used, azimuth and elevation and the distance that is range [11] [13]. These three parameters are defined as

- Elevation Angle ε (pitch): It is the angle calculated from the horizontal plane of the sensor in upward direction.
- Azimuth Angle α (yaw): It is the counterclockwise angle measured from the x-axis of the sensor.
- Range: It is defined as the distance from the lidar to the point. This range is calculated using the Time of flight (TOF) principle explained above [13].

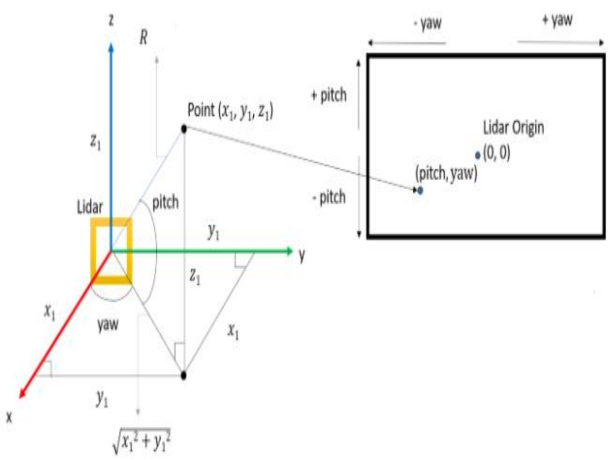

Fig. 5. Lidar point cloud projection

Analyzing the fig. 5, we can easily deduce coordinate transformation. If we look closely at the above figure, we can visualize if we consider positive x-axis as the front view of lidar sensor, then each value of point cloud will form an elevation angle pitch with the x-y plane and another angle azimuth angle yaw with the x-z axis. By coordinates transformation and trigonometric ratios, we can easily formulate the formula for calculation of elevation angle (ε), azimuth angle (α) and range (r) [12][13].

$$r = \sqrt{x^2 + y^2 + z^2} \quad (2)$$

$$\alpha = \tan^{-1} (y/x) \quad (3)$$

$$\varepsilon = \sin^{-1} (z / \sqrt{x^2 + y^2 + z^2}) \quad (4)$$

By using the above formulae in eqn. 2,3,4 we can calculate the required coordinate values for each point. As in fig. 4 origin is at the center of the image, the azimuth angle yaw and elevation angle pitch values accounts for the pixel position of the projected image. Thus, by finding the values for azimuth and elevation for each point, it is possible to form the image. Range will be utilized in the calculation of distance. In this way lidar generally works as a two-way sensor calculating both distance and creating image of the obstacle.

A point cloud is essentially a simplest form of 3D model. It is the collection of individual points plotted in 3D space. Each point contains several measurements, which includes coordinates data, color value in the form RGB (Red, Green, Blue) and luminance value. It basically works by performing scan on the object structure [13]. Scans are completed through a laser scanner. They work by sending pulses of light to an obstacle and measures how long it takes for each pulse to reflect back to the scanner. These measurements are used to detect the exact position of the points on the object and these points, then create the point cloud for 3D visualization.

B. *Power of Lidar*

For a photodetector to successfully capture the laser from a pulse laser emitter junction, it is transmitted and is weakened through the transmission medium. From there, it diffuses and is reflected from the target surface. It is then captured by the reception optic and is then processed into an electrical signal [4][8]. The power of a laser return is received at distance R and can be calculated as.

$$P(r) = E_p \, . \, (c\eta A/2r^2) \, . \, \beta \, .T(r) \quad (5)$$

here,
c = speed of light
E_p = energy of transmitted pulse laser
β = reflectivity of the target surface
η = overall system efficiency
T(r) = transmission loss through transmission medium

Here, β and T(r) are further calculated. β is the target surface's reflectivity and it is dependent on incident angle and surface properties. having reflectivity of 0 < Γ < 1 in a simple case of Lambertian reflection, β is given as:

$$\beta = \Gamma / \pi \quad (6)$$

Lambertian surface for reflection may be defined as a surface which when viewed from all the directions appears to be uniform. It reflects the entire incident light upon it. It is the property possessed by a diffusely reflecting surface. Furthermore, Transmission loss can be calculated with the help of the following equation.

$$T(r) = \exp[-2 \int_0^r \alpha(r) dr] \quad (7)$$

Here, $\alpha(r)$ = extinction coefficient of transmitting medium

This is because of the presence of particles in the transmission medium which are responsible for the scattering and absorption of the laser [8]. From equation 5 it is evident that the power received will be decreased quadratically. One solution is to increase the power of the laser transmitter. Due to safety standards and to prevent the naked eye this idea is not applicable. To resolve this issue, overall system efficiency must be improved through the use of advanced signal processing algorithms, optics, and state of the art photodetectors [4].

III. Components of a Lidar

A general lidar consists of mainly three main parts.

- Transmitter (Laser Source)
- Receiver (Detector)
- Time control and signal processing circuit

Usually, it is driven by a controller which includes a microcontroller or a FPGA sometimes. A pulsed laser is transmitted via a transmission medium, for example, air to illuminate the surrounding. When the emitted laser bounces back off from an obstacle, reflected or diffused laser returns and is collected by the optical system of the receiver. This received laser is then transformed into an electrical signal by sensors like photodetectors such as an Avalanche photodiode [8].

A. Laser Source

A pulse laser signal for a lidar (TOF) is generated using the following sources.

1) Fiber Lasers

They use optical fiber for lasing. Fiber lasers possess large active region so as to provide high optical gain. The advantages and benefits of a fiber laser includes its pulse width, beam delivery and pulse repetition rate. However, its high cost may be regarded as a disadvantage [2].

2) Microchip Lasers

Microchip lasers are solid state lasers that consists of a piece of doped glass or crystal working there as gain medium. Microchip lasers maintains balance between maximum power and pulse time duration, which makes them suitable for a wide range of applications [2].

3) Diode Lasers

They are the most common types of lidar sources that are used because of its compact structure and cheap cost. The ones which are used in automotive industry are hybrid devices. Laser chip is mounted along with capacitors which are powered by transistors. Thus, at every gate pulse, energy will flow into the capacitors which will be released into the laser chip. This laser chip in turns emits optical pulses as per requirements [4].

B. Photo Detectors

A detector is a sensor that is used to convert an optical signal into an electrical signal. They work on the principle of photoelectric effect. The most popular detectors are Avalanche photodiodes, p-i-n photodiodes and Single photon avalanche photodiodes (SPADs) [4].

1) Avalanche Photodiode

An avalanche photodiode works by applying reverse voltage so as to multiply photocurrent through avalanche effect [4].

2) Single Photon Avalanche Photodiode

A single photon avalanche photodiode (SPAD) is fabricated to operate with a reverse bias voltage above the breakdown voltage. SPADs can attain a gain value of 10^6. An integrated array of photodiodes can be fabricated on a single chip due to CMOS technology [2].

3) PIN Photodiode

A PIN photodiode consist of a wide intrinsic undoped semiconductor region between p and n regions. The PIN diode is reverse biased when it is used as a photodetector. Under normal conditions, diode does not behave as a conductor. But a high energy photon creates an electron-hole pair by entering into the depletion region. The field of the reverse bias region moves the carrier out of the region resulting in creation of current proportional to the incoming photons. This in turn gives rise to a photocurrent which is sent to an external amplification circuit [2].

C. Timing and Signal Processing

This part of the lidar sensor generally performs signal processing algorithms and signal conditioning on reflected pulses from obstacles. Power compensation and signal conversion takes place here. This section also filters the signal [4]. Analog to digital converters (ADCs) is also there to convert narrow lidar pulses to discrete values for the processor to process and for the purpose of data storage. Also, those ADCs require large analog input bandwidth and fast sampling rates. The shifted version of the received signal with the original signal is checked and compared with the phase comparator [7]. A suitable processing unit such as microcontroller or FPGA is used for processing of input and output generation.

IV. Types of Lidar

On the basis of scanning methods and imaging, lidar can be categorized into two main categories which includes Time of flight (TOF) lidar and Frequency modulated continuous wave (FMCW). The most widely used is lidar which employ TOF principle.

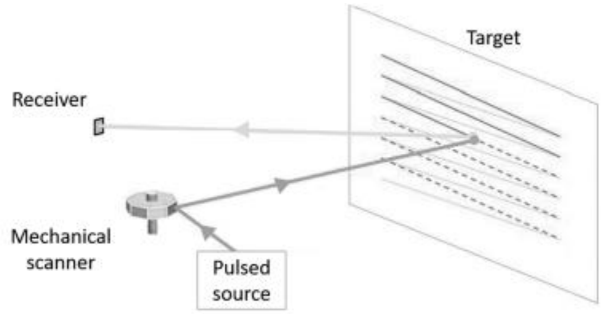

Fig. 6. Spinning type mechanical scanning lidar

A. Mechanical Scanning Lidar

This type of lidar imaging is based on mechanical scanners. This technology of imaging was the first to be used in lidar and is still popular despite improvements in scanning methods. This is very popular technique employed by renowned manufacturers like Velodyne. This type of lidar comprises of moving parts and is rotated with the help of motor to create a wide 360° field of view (FOV) [4]. However, vertical FOV is around 40 degrees only. So, they will cover the vertical area in this case. For the mechanical spinning lidar, 360 deg view is provided by rotating the lidar. To take an example: in velodyne we have vertical plane of 64 lasers. So, they will cover the vertical area in this case. Velodyne VLP series use series of photodiodes and laser diodes to have more point cloud densities. Despite its high resolution, its bulkiness, high costs and lack of robustness will prevent its widespread adoption. It consumes a lot of power as compared to other scanning methods. Moreover, size is also a big issue when considering mechanical scanning lidar. Fig. 6 shows the structure of a simple mechanical scanning lidar [2].

B. Micro Electro Mechanical Scanning Lidar

Micro electro mechanical scanning (MEMS) system lidar is considered as a semi solid state lidar due to its fewer moving parts. These types of scanners can be produced in a bulk quantity and a relatively lower cost using Silicon (Si) fabrication technique. It consists of a MEMs mirror which is embedded on a chip. Fig. 7 shows the working of a MEMs lidar. The MEMS mirror is rotated by balancing between two opposing forces: an electromagnetic force (Lorentz force) produced by the conductive coil around the mirror and an elastic force from a torsion bar, which serves as the axis of rotation. The low moment of inertia (MOI) enables MEMs mirror to perform a 2D scan in a fraction of seconds over the entire field of view (FOV) [5]. As per the working principle, a MEMS lidar will have limited horizontal and vertical field of view. In order to compensate for this multiple units are required to have maximum coverage. Despite being a electromechanical system, due to its advantages like low cost, manufacturing ease, light weight, cost and compact structure, MEMs lidar have received major attention. Two companies namely Innoviz and Innoluce are providing MEMs based lidar solutions [2][5].

C. Optical Phased Array

Optical phased array is a perfect solid-state scanner which consists of zero moving parts and is based on Photonics Integrated Circuits (PIC) to steer the laser beam. The light speed can be modified using phase modulators. Fig. 8 illustrates how various light beams in different paths enables control of wavefront shape and orientation leading to a larger steering angle at high speed. However, as far as autonomous driving is concerned, OPA based lidars are still under experimentation for long range lidar based object tracking and detection [2][4].

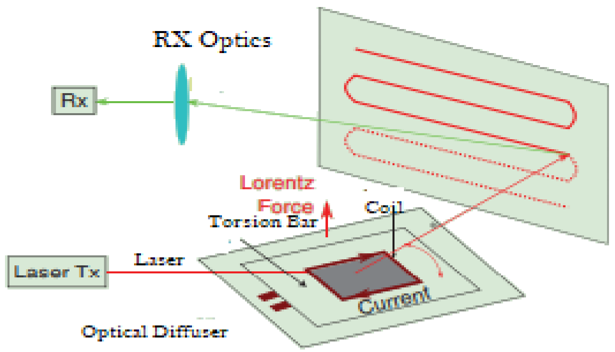

Fig. 7. MEMs lidar [4]

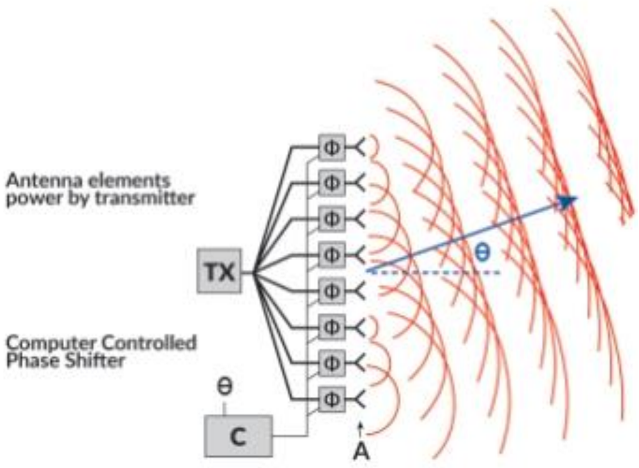

Fig. 8. OPA lidar [4]

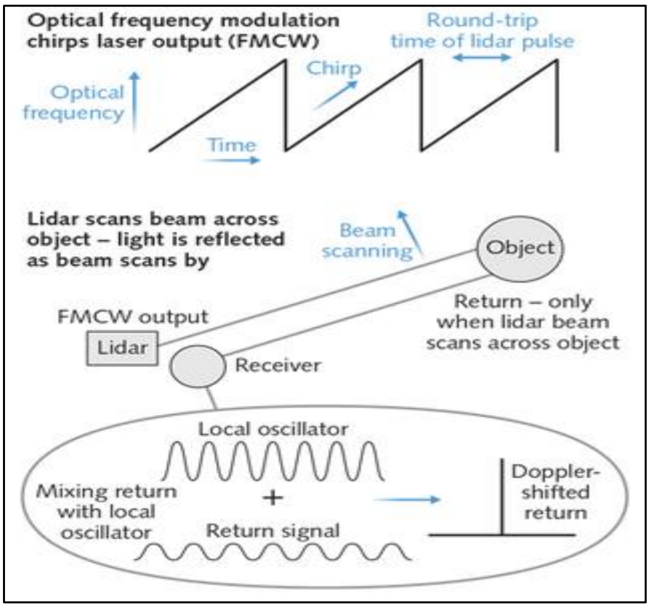

Fig. 9. FMCW lidar [14]

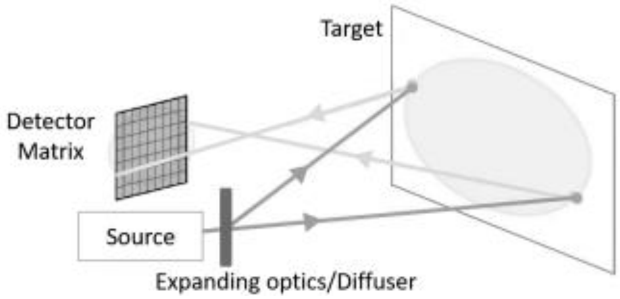

Fig. 10 Flash lidar [2]

D. Frequency Modulated Continuous-wave Lidar

FMCW lidar calculates the distance by chirping frequency of the continuous beam of laser repeatedly. Usually, the time taken by light to reach the object is lesser than the chirp rise. As it scans past it reflects the beam. The local oscillator is mixed with the return signal, by a coherent detector and frequency difference is measured. This frequency difference shows how much the value of frequency has changed while reflected light made its complete round trip. If we multiply that interval by chirp speed, it will result in distance calculation. An added feature is velocity calculation that is obtained by further processing which extracts the doppler shift resulting in object's velocity with respect to lidar. This feature keeps autonomous vehicles aware of other moving obstacles and vehicles around them [14]. Figure 9 shows excellent explanation of details mentioned above.

The key advantages of of FMCW lidar techniques includes velocity sensitivity, single photon sensitivity and improved range resolution. Here improved range resolution means the separation and measurement of various closely lying surfaces. One of its drawbacks is its range which is about 50m which hinders it usage in autonomous vehicle architecture [14].

E. Flash Lidar

A flash lidar works in the same manner like a camera because of the fact that it uses an optical flash. This is a true solid-state type of sensor with nonmoving parts. A single laser is scattered by an optical diffuser to lighten the whole scene. Then it utilizes a 2D array of photodiodes like a CMOS to detect the laser return from the object as detecting mechanism. These laser points are then processed to form 3D point cloud. The detector here is a special CMOS array or in some cases one dimensional or two-dimensional (2D) array of photodiodes which are situated at the focal plane of detecting optic mechanism. Fig shows the working of flash lidar in detail. This method acquires the entire target scene in a single image, the data acquisition rate is much faster than others. In addition, vibration effects are minimized as the entire image is acquired in a single go. Moreover, the semiconductor-based 3D flash lidar eases fabrication and packaging leading to overall lower cost. A demerit of this system is typical low range which is typically less than 100 m as a matter of fact that a single diffused laser is detect the whole area under less power threshold for safety of human vision [4]. Another disadvantage of this system is the retroreflectors presence in the real world environment. Retroreflectors back scatters very little light and reflects most of it, in effect binding the whole sensor and making it less fruitful [1].

V. CONCLUSION

In this paper, lidar sensor and its application in autonomous driving architecture is presented. The world is moving to a whole new transitioning towards development of autonomous vehicles. Lidar being used in this industry from late 2000s is a key player in the design of autonomous vehicles. The key concept how lidar visualizes the world and the main developments in lidar industry are discussed. Different technologies involved in lidar scanning system and sections are discussed. Distance measurement and 3D visualization of surrounding gives it an edge over other vision sensor. Like in camera, only 2D manipulation of image exists where as in radar it can only measure distance to the object. Moreover, the concept of sensor fusion that is combining different sensors performance and data makes lidar an integral part of an autonomous vehicle architecture. However, certain limitations such as performance in bad weather conditions for example fog and rain, and range acquisition greater than 200 m for highway driving still needs to tackled by researchers and innovators involved in the field of optics and photonics.

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REFERENCES

[1] Khader, S. C. M., and S. Cherian. "An introduction to automotive light detection and ranging (LIDAR) and solutions to serve future autonomous driving systems." (2020).

[2] Royo, Santiago, and Maria Ballesta-Garcia. "An overview of lidar imaging systems for autonomous vehicles." Applied sciences 9, no. 19 (2019): 4093.

[3] Hecht, Jeff. "Lidar for self-driving cars." Optics and Photonics News 29, no. 1 (2018): 26-33.

[4] Y. Li and J. Ibanez-Guzman, "Lidar for Autonomous Driving: The Principles, Challenges, and Trends for Automotive Lidar and Perception Systems," in IEEE Signal Processing Magazine, vol. 37, no. 4, pp. 50-61, July 2020, doi: 10.1109/MSP.2020.2973615.

[5] Rablau, Corneliu. "LIDAR–A new (self-driving) vehicle for introducing optics to broader engineering and non-engineering audiences." In Education and Training in Optics and Photonics, p. 11143_138. Optical Society of America, 2019.

[6] Chen, Xieyuanli, Ignacio Vizzo, Thomas Läbe, Jens Behley, and Cyrill Stachniss. "Range Image-based LiDAR Localization for Autonomous Vehicles." arXiv preprint arXiv:2105.12121 (2021).

[7] Khairul, I., and A. Bhuiyan. LIDAR sensor for autonomous vehicle. Technical report, Technische Universität Chemnitz, 2017.

[8]]Y. Li, P. Duthon, M. Colomb and J. Ibanez-Guzman, "What Happens for a ToF LiDAR in Fog?," in IEEE Transactions on Intelligent Transportation Systems, doi: 10.1109/TITS.2020.2998077

[9] CVEL, "Clemson Vehicular Electronics Laboratory: Autonomous Vehicles,"[Online]. Available: https://cecas.clemson.edu/cvel/auto/AuE835_Projects_2011/Vallabhaneni_project.html. [Accessed 10 07 2021].

[10] ASIRT, "Road Safety Facts — Association for Safe International Road Travel," [Online]. Available: https://www.asirt.org/safe-travel/road-safety-facts/. [Accessed 07 07 2021].

[11] Lihui Wang and Baozong Yuan, "Curvature and density based feature point detection for point cloud data," IET 3rd International Conference on Wireless, Mobile and Multimedia Networks (ICWMNN 2010), 2010, pp. 377-380, doi: 10.1049/cp.2010.0694.

[12]] T. d. science, "Spherical Projection for Point Clouds | by Anirudh Topiwala | Towards Data Science," [Online]. Available: https://towardsdatascience.com/spherical-projection-for-point-clouds56a2fc258e6c. [Accessed 10 07 2021].

[13] T. A. World, "Spherical & Cartesian Frames for 3D LIDAR sensor measurements | The Autonomous World," [Online]. Available: https://theautonomousworld.com/spherical-cartesian-frames-for-3dlidar-sensor-measurements/. [Accessed 10 07 2021].

[14] L. F. World, "Lasers for Lidar: FMCW lidar: An alternative for self-driving cars | Laser Focus World," [Online]. Available: https://www.laserfocusworld.com/home/article/16556322/lasers-for-lidar-fmcwlidar-an-alternative-for-selfdriving-cars. [Accessed 11 07 2021].