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Pursuit for a Fully Autonomous Automotive - LiDAR Leads the Battlefield: Its Principles, Challenges, Trends and Perception System

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Abstract: The global automotive industry is always a fast growing and highly competitive field as every participant involved relentlessly thrives to achieve technological advancement of their product and solution to stand-out among the rest. Lately, the pursuit towards developing a fully autonomous car has intensified manifold among all the automakers because of the increasing need for advanced driving assistance and safety. In the era of AI advancements, self-driving cars is so much more challenging that most people expected. Autonomous vehicle requires L3 or higher level smart connected capability to function efficiently and LiDAR is at the forefront in serving the requirement. This paper is set to explicitly furnish all the technical and functional development of a number of LiDAR technologies in existence in the automotive ecosystem and also systemically distinguish and analyze each of them. In addition, this paper provides recent advancement and development of key automotive LiDAR technology, startups, trends and how far are we behind from reaching the ambition of becoming a permanent backseat driver.
Keywords: Autonomous vehicle, LiDAR, Automotive industry, Industry growth.

I. INTRODUCTION

In recent years, LiDAR (an acronym of light detection and ranging) has emerged as a new pot of gold in the field of optoelectronics and optomechanical Engineering from merely a measurement technique used in the studies of aerial mappings and atmospheric aerosols. Evidentially, LiDAR technology has its own data format (. LAS, for laser) for data exchange across sensors and software. Numerous startups which set foot in this field is receiving heavy investments from the venture capital sector while few successful ones are being acquired by established industrial corporations, specifically in automotive field. The main reason is the increasing market-pull of fully-automated (self-driving) car and the demanding necessity to bridge the existing gap that’s underlying the present LiDAR technology in the market for automation like performance, cost and industrialization. LiDAR works on Time-of-Flight principle which basically measures the time difference between the time light energy is emitted to the time it is diffracted from a target. However, the capability of this technology is limited without its dependency on other key advancements in recent times like 3D cameras. LiDAR together with 3D cameras are already being used in audiovisual segmentation, RGB+depth fusion, 3D screens, people, Object detection and human-machine interface (Microsoft Kinect). But the image's spatial and depth resolution limitations restrict it to large-scale subjects (like humans). This LiDAR system has already started to revolutionize automotive industry in the form of fully-automated car. The dream of driving a car without human intervention has begun to come true for traveling on the highways and parking. The advantages of autonomous cars are overwhelming and it is expected to reduce fatalities due to human errors by 90%. Furthermore, with adequate standardization of roads and traffic issues, self-driving cars can be made accessible for the disabled and older individuals. For a full-scale automation, the one which can anticipate all possible situations, we need a coordinated system that can combine LiDAR with video cameras and radar assisted by deep learning. However, for automotive applications because of requirements like long-range, tolerance to daytime solar background, real-time performance and high spatial resolution it is still in incumbent stage of development to becoming a feasible technology in self-driving cars. Rotating LiDAR imagers is the first major breakthrough in automotive field which demands various potential usage cases for practical application. It uses a rotating wheel configuration to include short and long-range, or wide and narrow fields of view. But when it comes to industrializing the sensors, it is not practically viable to attain a final low-cost unit or a compact sensor to accommodate inside a car. So, the quest for using a fully functional LiDAR driven autonomous car is far from reach at the moment.
Hence, the main scope of this paper is to objectively analyze the underlying principles and current capabilities with drawbacks of different LiDAR driven systems specifically in automotive sector.

II. CANONIC OF LIDAR IMAGING SYSTEM IN AUTOMOTIVE

Its Time-of flight (TOF), operating principle provides location data by calculating the transit time of scattered photons. LiDAR system actively transmit signal in the form of photons onto the target and create a 3D point cloud based on the distance calculated through TOF. The range or distance R calculated during TOF is the time taken by the emitted light to travel and hit the target to the time when it is received back by the receiver. To achieve a better 3D point cloud, the phase, intensity and frequency of the emitted photons has to be adjusted.

A. Pulsed Technique

Short pulse which usually lasts for nanoseconds are used to achieve wide window ranges in centimeter level because of its high intensity peak power. TOF in pulsed approach is calculated by the formula,

$$R = (C/2)t_0F$$

where R is the range to the object, c is the speed of light (c = 3 × 10^8 m/s) in free space and t_0F is the time taken by the emitted photons to travel back to the detector after emission.

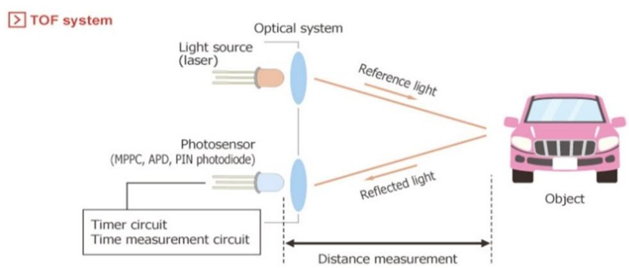

Fig. 1 Pulsed technique for measuring TOF

With c being constant, Range R is directly proportional to the time taken for the light to reach the detector t_0F. So, when it comes to least possible depth measurement in pulsed technique, it depends entirely on the capability of timer circuit to detect the signal after considering jitter and noises in the device. At present, it is assumed as 1.5 cm depth but this can considerably be increased compromising frame rate and spatial resolutions by pulse per data point. When it comes to maximum attainable limit, it is scaled at 150 m. There are few factors which contribute to this, like loss in energy due to diffusing targets, bandwidth compatibility of detecting sensors, signal-to-noise ratio (SNR) and the presence of simultaneous pulse in emitted photons to the target. Since pulsed technique depends entirely on the time taken by the emitted pulse to be detected back on the detectors, there will always be a loss in energy of the transmitted pulse in contrast to the return pulse. So, the detector used should be very sensitive to capture even the weakest of signals at very high frequency. Despite these short comings, pulsed approach is the most commonly proposed LiDAR technique among manufactures of self-driving cars because of its less complexity and the capability to perform outdoor.

B. Amplitude Modulated Continuous Wave

In case of Amplitude Modulated Continuous Wave (AMCW), the distance is measured by analyzing the phase difference of transmitted and received photons from the source. Though its precision can be in par with pulsed approach, it is very much limited to moderate range because of frequency modulation's 2π ambiguity while digitization of long range is not feasible. And also, the strength of photons received at the detector is not strong because of continuous emission and any attempt to intensify the strength is compromising to the safety limit of eyes.

The modulation of optical frequency $f_m$is usually in the constant range of some tenths of MHz and superposition helps to identify the phase shift $\Delta\phi$ between two signals. TOF in AMCW is calculated by the formula,

$$\Delta\Phi = k_M d = \frac{2\pi f_M}{c} 2R \Rightarrow R = \frac{c}{2}\frac{\Delta\Phi}{2\pi f_M},$$

where R and c are the range to the object and the speed of light; k_m is the wavenumber associated to the modulation frequency, d is the total distance travelled and f_m is the modulation frequency of the amplitude of the signal.

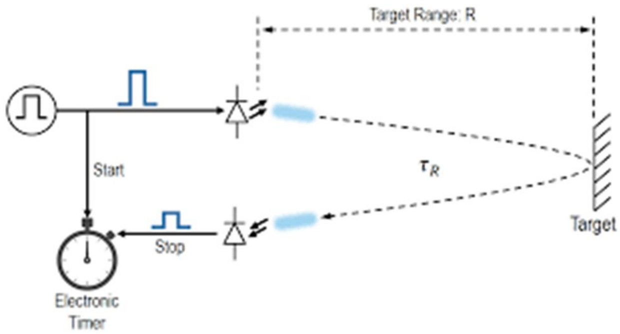

Fig. 2 AMCW approach TOF measurement

Resolution in this approach is dependent on two factors, frequency f_m of the actual ranging circuit and the resolution capability of the phase meter in electronic timer. By keeping the resolution of phase meter constant, maximum resolution can be obtained. However, because of 2π unambiguity the resolution at shorter ranges will start to repeat the same value. Incidentally, methods using advanced modulated-intensity systems are used to increase the range. Depth accuracy needs longer time to counter the impact of SNR and because of this the demand to obtain faster frame rate becomes difficult. Despite these drawbacks, they serve good indoor capabilities in automotive where they are sometimes used in a number of applications, such as passenger or driver identification and vehicle interface.

C. Frequency Modulated Continuous Waves

This case overcame the difficulties of AWCW by enabling the modulation and demodulation of transmitted continuous waves from a laser diode and the captured wave forms are super imposed to arrive at the final image whose resolution in terms of range measurements can be as low as 150 µm while its precision can be as low as 1 µm in long range.

This final wave forms are compared with the reference waves forms to measure the time-of-flight (TOF). For a stationery target, the differences in wave forms of reference and collected light will be identical frequency f_r.

$$f_r = slope \cdot \Delta\tau = \frac{B}{T} t_{oF} = \frac{B}{T}\frac{2R}{c} \Rightarrow R = f_r \frac{cT}{2B},$$

where B is the bandwidth of the frequency sweep, T denotes the period of the ramp, and Δτ equals the total travelled time TOF.

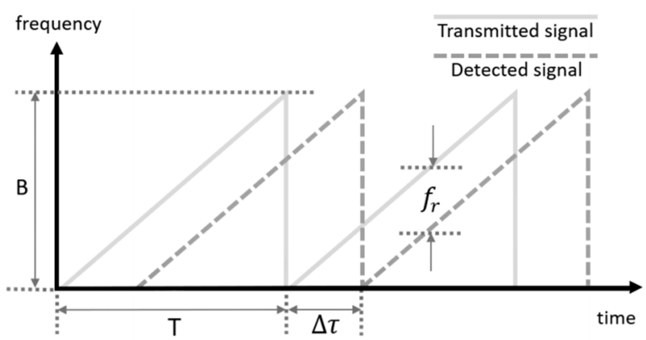

Fig. 3 Parameters involved in FMCW

An interference frequency pattern f_r in the form of a triangle is obtained because of periodic phase difference between transmitted and received photons. The resultant beat frequency is given by the formula:

$$f_r = \frac{4Rf_mB}{c}$$

Where f_m is the modulation frequency.

$$f^+ = f_r + f_d \text{ and } f^- = f_r - f_d.$$

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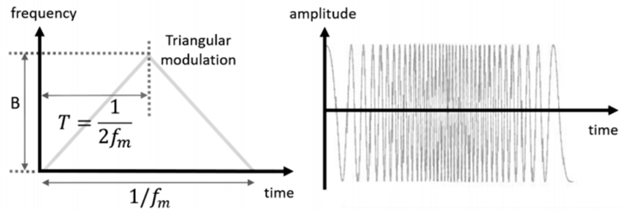

Fig. 4 Triangular frequency modulation with time and linked amplitude signal change in the time domain

In case of moving target, velocity v_r is also taken into consideration in the form of Doppler frequency f_d to obtain beat frequency f_r.

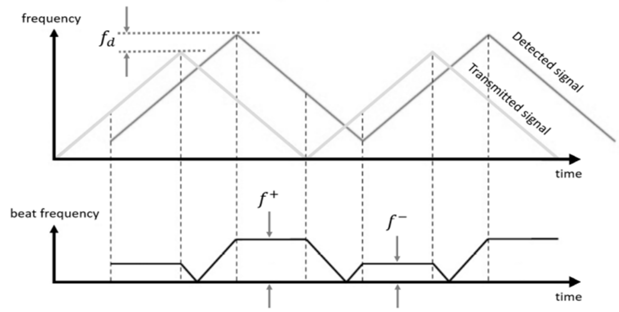

Fig. 5 Triangular modulation frequency signal and beat frequency for a moving target

Where Range is,

$$R = \frac{cT}{4B}\left(f^+ + f^-\right),$$

while relative velocity is,

$$v_r = \frac{\lambda}{2} f_d = \frac{\lambda}{4}\left(f^+ - f^-\right),$$

Due to its high bandwidth capability, better performance of the range sensor can be achieved in this method. Hence, the range of TOF can be obtained in picosecond or submillimeter distance in kilohertz. Despite all this, since this approach depends on the perfectly linear frequency sweep of control current, it is practically not possible to maintain linear frequency and most of the current are non-linear. Thus, this significantly affects the beat frequency f_r and in turn accuracy of the modulation slope is impacted. Unlike other two approaches, FMCW uses coherent detection in Fourier domain. This felicitates the use of FMCW in outdoor environment and has relatively better accuracy and long-range values compared to AMCW. Additionally, it has the capability to detect the speed and direction of the target. However, because of its coherent detection scheme, use of a suitable tunable laser capable of enduring extreme environment and stability in performance at high temperature and the ability to obtain accuracy of modulation electronics are not practically feasible.

	Pulsed	**AMCW**	**FMCW**
Parameter measured	Intensity of emitted and received pulse	Phase of modulated amplitude	Relative beat of modulated frequency, and Doppler shift
Measurement	Direct	Indirect	Indirect
Detection	Incoherent	Incoherent	Coherent
Use	Indoor/Outdoor	Only indoor	Indoor/Outdoor
Main advantage	Simplicity of setup; long ambiguity range	Established commercially	Simultaneous speed and range measures
Main limitation	Low SNR of returned pulse	Short ambiguity distance	Coherence length/Stability in operating conditions (e.g., thermal)
Depth resolution (typ)	1 cm	1 cm	0.1 cm

* Note: maximum attainable range has been avoided as it needs the definition of several other parameters (instantaneous FOV, reflectivity of target, eye safety level, etc.)

Table 1. Summary of working principles

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III. IMAGE PROCESSING

All three approaches produce target image with 360◦ field of view represented in 3D point clouds. However, they are classified into three different families:

A. *Scanner*

It is used in LiDAR system to adjust the angle of emitted light on to the target object to create 3D point cloud using a steering component. But this periodic changes in the angle of projected beam jeopardize the spatial resolution of the images. Most of the scanners used in autonomous vehicle LiDAR uses galvanometric mirrors and there are a number of scanners in commercial use but three main categories stand out on top.

1) *Mechanical Scanners:* This functions by using a rotating mirror and galvanometric positioning of mirrors attached to the mechanical actuator to cover a wide field of view while the emitter and the sensors rotate around the single axis covering the 360◦ fields of view. This method has the advantage of getting the 2D point cloud by increasing the number of detectors or the source of laser to measure different angular directions simultaneously.

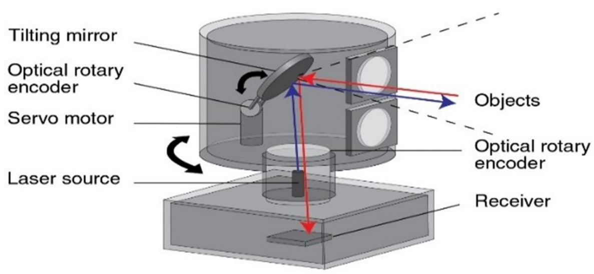

Fig. 6 Mechanical Scanners

Rotating source in mechanical scanner enable easier access to long-range because it has the potential to gather even the faint diffuse from the target object. It emitted photons are usually pulses and the entire scanner arrangement is very large and bulky. The spatial resolution is usually better along the direction of rotation of the rotating scanner. Although the resolution along the perpendicular axis can be improved by additional use of sources and detector. This method also consumes more energy input for operating the mechanical rotator and because of its bulkiness frame rate is also reduced to the range of 1 Hz to 100 Hz. Other major issues include reliability and maintenance mechanism, lack of scanning flexibility, shock and vibration misalignment-prone, operational cost and scalability. Despite all these drawbacks, most of the automotive manufacturers prefer mechanical scanning using different principles.

2) *Microelectromechanical Scanners:* This scanner allows programmable control of laser beam from tiny mirror whose diameter is usually in mm. It uses a stimulus to vary the angle of the light beam towards a specific target. This programmed control of beam can be two-dimensional (2D) to felicitate complete 360-degree field of view of the target object. Depending on the performance and application various stimulus like speed, angle, power and packaging capability a number of technologies are used but the voltage is the most common stimulus among other. Stored pattern generate drive voltages is used to steer the mirrors. Piezoelectric and electromagnetic actuator are the most commonly used type of stimulus. The size of the MEMS scanner is reduced by replacing the mechanical scanning hardware with electromechanical hardware. The field of view is reduced in electromechanical scanner, however by merging the data collected from multiple channels, better FOV can be achieved. Mirrors used in MEMS scanners are classified into resonant and non-resonant based on the operating mode. Trajectory design in non-resonant scanner provide large degree of freedom and at the same time they need a more intricate controller to perform effectively and also, they are not capable of controlling scanning angle. On the other hand, resonant scanners have really good control over scanning angle with relatively simple controlling mechanism but the trajectory is not uniform. 2D point cloud can be obtained by using a single mirror that can rotate along two axis or a dual mirror with each rotating along one axis. Single mirror is easier to operate and has the potential to operate in robust conditions while dual mirror provide optical and packaging benefits but the crosstalk between two axes mirror is a worrying factor here. Whenever there is a need to get a better point cloud resolution, it is not a good choice to use dual mirror configuration.

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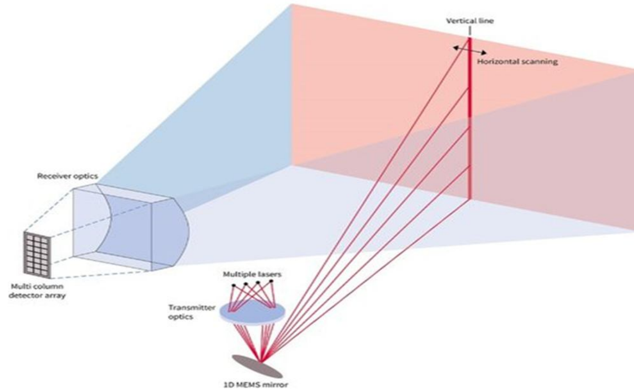

Fig. 7 MEMS Scanners

3) *Optical Phased Arrays:* This is a latest development in LiDAR system which enable us to steer the transmitting beam in multiple guided wave-form by tuning the phase of emitting source. A modulator regulates the speed of the light emitted from the source which enables to attain 3D point cloud at ease. This is the most effective method to control the wave form among other types. It nullified almost all the major setbacks in other types but it has big insertion loss. It also allows large steering angle of transmitting beam at higher speed because of the absence of inertia enabling it as an alternative to MEMS method. Because of the absence of any moving parts, they can be used in extreme conditions and also their small size enable the manufacturers to contain it inside a single chip.

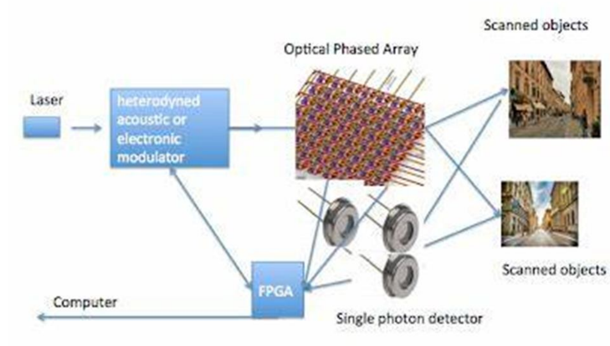

Fig. 8 Optical phased arrays

However, they cannot handle bulky operation that demands high processing speed because of the lack of power density. Recent breakthrough in LiDAR technology has made OPA ideal even for high power densities.

B. *Detector Arrays*

Limitations in scanning-based LiDAR technology has paved the way for alternate LiDAR systems in automotive industry, one such approach is detector array which uses an array of receivers instead of mechanical scanner. It operates by transmitting the photons on to the target object and in turn the detector receives the reflected signal that has varying frequency to arrive at the final image. The illumination technique can either be continuous or pulsed.

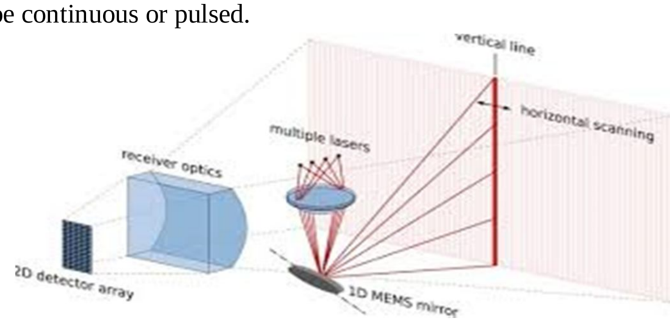

Fig. 9 Detector arrays

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1) *Flash Imagers:* It is one of the most promising lidar imaging system used in autonomous vehicle for short and medium range commercial uses. In this approach, pulsed laser source is flooded on to the target object and the reflected light is detected by the array of detectors which is capable of detecting individual beam of flashed light thus both optical image as well as 3D point cloud is obtained from this approach. Here FOV of the illuminating source and the detector array has to be aligned properly by using a divergent optical system to get maximum range. The alignment of source beam is with respect to the detector arrays to capture maximum FOV. The detector captures both range and intensity of the incoming reflected beam. The spatial resolution depends on the detector's CMOS pattering scheme. Usually, it is as less as tenths of Kilopixels due to the use of focal plane in detector. Single photon avalanche diodes however restrict its usage to small and medium level applications in autonomous vehicle. They pose a major problem in real world scenario where the use of retro-reflector floods the amount of back-scattered light from the target which will saturate the detector signal. On the plus side, flash imagers have the capability to capture entire target in single picture and has the benefit of working in rugged working conditions has made it a potential alternative in automotive industry.
2) *AMCW Camera:* The detector array uses the TOF camera to capture AMCW laser beam from the source wherein the intensity of the transmitted photons is modulated and the phase difference of the signal received by the detector is analyzed at least four times across each detector. This approach also uses CMOS detector because of its short-distance capability to measure few centimeters to several meters. The TOF camera used in this method are modulated to work around infra-red range and are not ideal for eye-safety. This approach is not suitable for external applications due to the effects of background light on the detector. But they are ideal for indoor use and they are already used in passenger detection inside automotive.

C. Miscellaneous Approaches

Some of the manufacturers have come up with the combination of the above two approaches to make use of the advantages of each approach. One such approach is spinning-lidar where single rotating axis is used with vertical array of emitters and detectors to balance the issue in traditional scanner. This strategy increases the frame rate and the quantity of data capture while also increasing the FOV over long distances. Another approach is flash LiDAR with multiple arrays of detector mounted on a rotating mechanism to obtain 360-degree field of view. One more successful approach is the use of MEMS mirror to project a 1D beam on to the target and detect either 1D or 2D images on the detector which significantly reduces the size and weight while also avoid bulky macroscopic movement.

Table 2. Summary of all approaches

	Mechanical Scanners	**MEMS Scanners**	**OPAs**	**Flash**	**AMCWs**
Working principle	Galvos, rotating mirrors or prisms	MEMS micromirror	Phased array of antennas	Pulsed flood illumination	Pixelated phase meters
Main advantage	360 deg FOV in horizontal	Compact and lightweight	Full Solid State	Fast frame rate	Commercial
Main disadvantage	Moving elements, bulky	Laser power management, linearity	Lab-only for long-range	Limited range/Blindable	Only indoor

IV. LATEST TECHNICAL VOGUE FOR AUTONOMOUS VEHICLE USING LIDAR TECHNOLOGY

As we know, the basic LiDAR system comprises of a source, detector, data processor, and a suitable strategy to gather information to create 3D maps. With various canonicals and image processing techniques being discussed so far, there are only a few approaches most preferably employed in real world commercial applications in automotive industry.

A. Sources

The LiDAR used in autonomous cars are usually in infra-red range (0.80 to 1.55 µm) to make use of atmospheric transmission window. Various sources in practice are selected solely based on their performance.

1) Fiber Laser
2) Microchip laser
3) Diode laser

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Table 3. Summary of LiDAR sources

	Fibre Laser	Microchip Laser	Diode Laser
Amplifying media	Doped optical fibre	Semiconductor crystal	Semiconductor PN junction
Peak power (typ)	>10 kW	>1 kW	0.1 kW
PRR	<1 MHz	<1 MHz	≈100 KHz
Pulse width	<5 ns	<5 ns	100 ns
Main advantage	Pulse peak power, PRR, beam quality. Beam delivery	Pulse peak power, PRR, beam quality	Cost, compact
Main disadvantage	Cost	Cost, beam delivery	Max output power and PRR. Beam quality

B. Photodetectors

It is a key sensing device in LiDAR system to sense the reflected beam of photons from the target to calculate the TOF. It should have a high sensitiveness to detect short pulses with high intensity. There are a number of detector variants in commercial use from single-element detectors to array of 2D detector. Some of the most popular ones used in automotive industry are

1) PIN photodiodes
2) Avalanche photodiodes
3) Single-photon avalanche photodiodes
4) Multipixel photon counters
5) Photomultiplier tubes

Table 4. Summary of photodetectors

	PIN	APDs	SPADs	MPPCs	PMTs
Solid state	Yes	Yes	Yes	Yes	No
Gain (typ)	1	Linear (≈200)	Geiger (10^4)	Geiger (10^6)	Avalanche (10^6)
Main advantage	Fast	Adjustable gain by bias	Single photon detection	Single photon counting	Gain, UV detection
Main disadvantage	Limited for low SNR	Limited gain	Recovery time	Saturable, bias voltage dependence	Bulky, low QE, high voltage, magnetic fields

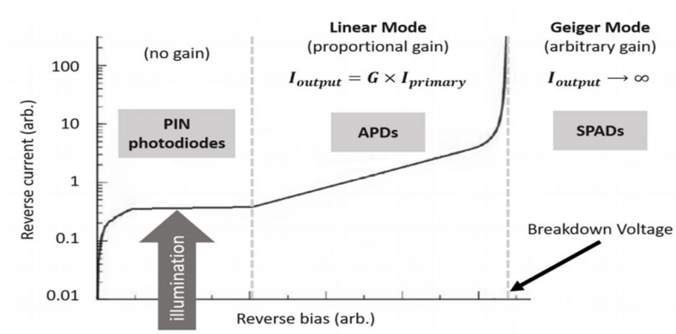

Fig. 10 Schematic I-V curve in different photodetectors showing the different behavior of gain

V. DEMOGRAPHICS WHICH INFLUENCE THE DYNAMICS OF LIDAR INDUSTRY GROWTH

At the moment the volume and revenue share of LiDAR in automotive industry around the globe is surging exponentially because of its increasing potentials in 3D imaging and mapping applications. LiDAR market share is expected to surge over 3.21 Bn USD over a span of next 5 years as per Global market insight.

A. Continuous Efforts By Major Business Leaders

Some of the key players in LiDAR technology in the market are Geodigital, Leddartech, Quantum Spatial, Topcon Positioning Systems, and Innoviz Technologies amongst others. They are relentlessly working on finding a breakthrough in this field to push themselves to the top. Continental – AG, has invested massively into Robotics vision and sensing pioneer – AEye to broaden its horizon in LiDAR field. As a result, they have come up with an innovation that can sense small, low-reflective objects at a distance of almost 160 meters apart which can be used for autonomous driving. It is expected that Continental is planning to mass produce their breakthrough to commercialize their proven LiDAR technology.

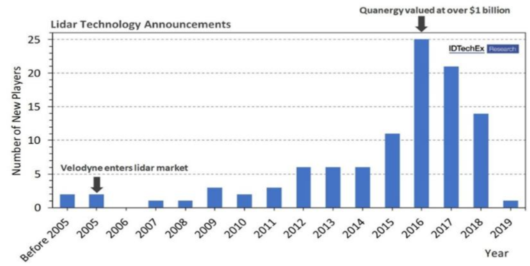

Fig. 11 Market forecast on LiDAR

B. Proliferating Technology used in Autonomous Vehicles

With rising scope of LiDAR in automotive industry and autonomous vehicle, mechanical segment of LiDAR technology has surged at a novel rate. As per a report, because of the rising trend for self-driving cars market share of mechanical segment has surged 90% in the year 2018.

Presently, automotive industries are using LiDAR technology in the field of advanced driving assistance of semi-autonomous car to increase safety.

C. Expansive Presence of Automakers in North America

US automakers alone contributed to around 50% of the entire globe's LiDAR investment in the year 2018. It is attributed to the presence of increasing number of automakers and the increase in large number startups in LiDAR field. Drones and recreational purpose applications also plays a major role in projecting US as an expansive kingdom of LiDAR.

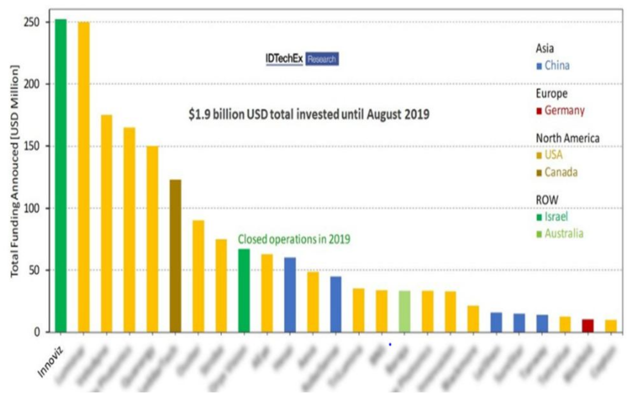

Fig. 12 Investment on LiDAR

D. Increased LIDAR use for Environmental Purposes

With increasing environmental issues, as per a report, environment segment is expected to grow manifold in the coming year. LiDAR is used in intrinsic geoscience applications for precise and high-quality point clouds and analyze the density of wildlife ecosystem. They are also extensively used in topographical applications which is expected to grow 25% over the coming future.

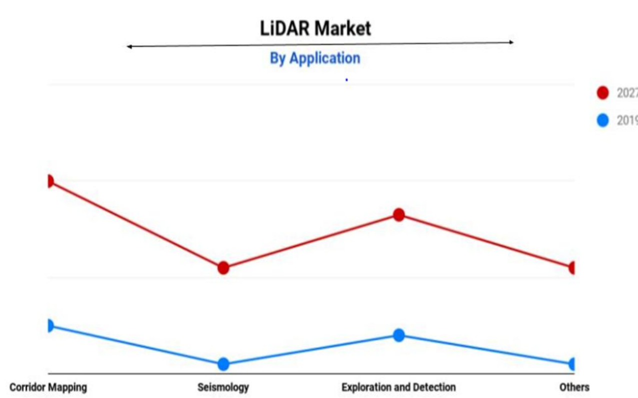

Fig. 13 Market forecast of LiDAR on environmental issues

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VI. FORECAST OF AUTOMOTIVE LIDAR MARKET

The global LiDAR market was valued at $700.2 million in 2019, and is projected to reach $2.90 billion by 2027, growing at a CAGR of 20.1% from 2020 to 2027.

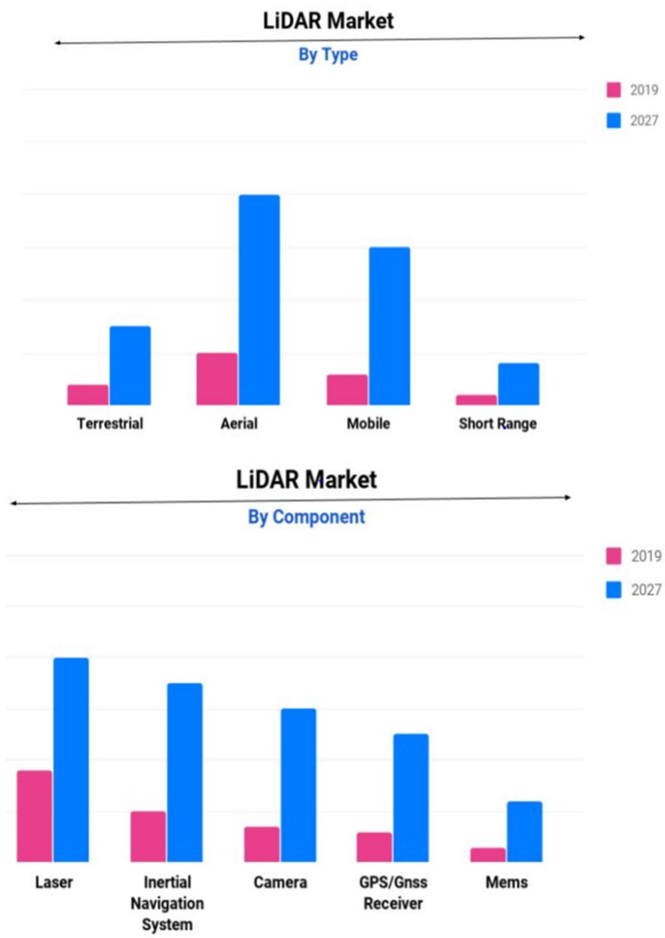

Fig. 11 Forecast on Automotive LiDAR market

VII. CONCLUSION: A VISION FOR IDEAL FUTURE SYSTEM

As most people expected, the aspiration of becoming a permanent backseat driver is still a far cry. Leading automakers had promised to put their self-driving cars on the street in 2020, but we are here and only few make it to the streets on trial programs. All the optimism researchers and engineers had on AI dropped when they started experimenting in real world scenario on self-driving cars because AI need billions of hours of footage of a car to develop an algorithm of its own.

Still, the pursuit for technological advancement in LiDAR field continues to grow and different players are coming up with different roadmaps of their own. Especially in automotive segment encompassing a number of approaches and strategy among which FMCW is a coherent detection technology preferred by prominent automakers because of its 4D information and high-resolution range using photoelectric detector which is relatively cheap. In the coming years, LiDAR vendors around the globe are working tirelessly to commercialise above L3 sensors for autonomous driving.

Few researchers believe that autonomous vehicles are going to save the environment as they would drastically increase car trips by making car ownership needless and make transitioning society where people would use their phone to call a car whenever they need and also, they would reduce human errors completely which is a major cause of death (road accidents) around the world. However, there is no federal law in any parts of the world in governing the development and implementation of autonomous cars.

Various manufacturers are making number of claims and it would be difficult to get a good estimate of how far are we from attaining a fully functioning self-driving car as most manufacturers are known to publicise good numbers for incentives. It’s not hard to expect self-driving car next year at least in sufficiently little contexts. Nonetheless, self-driving cars are a real possibility and we’re closer than a year ago but when they’ll actually get here is anyone’s guess.

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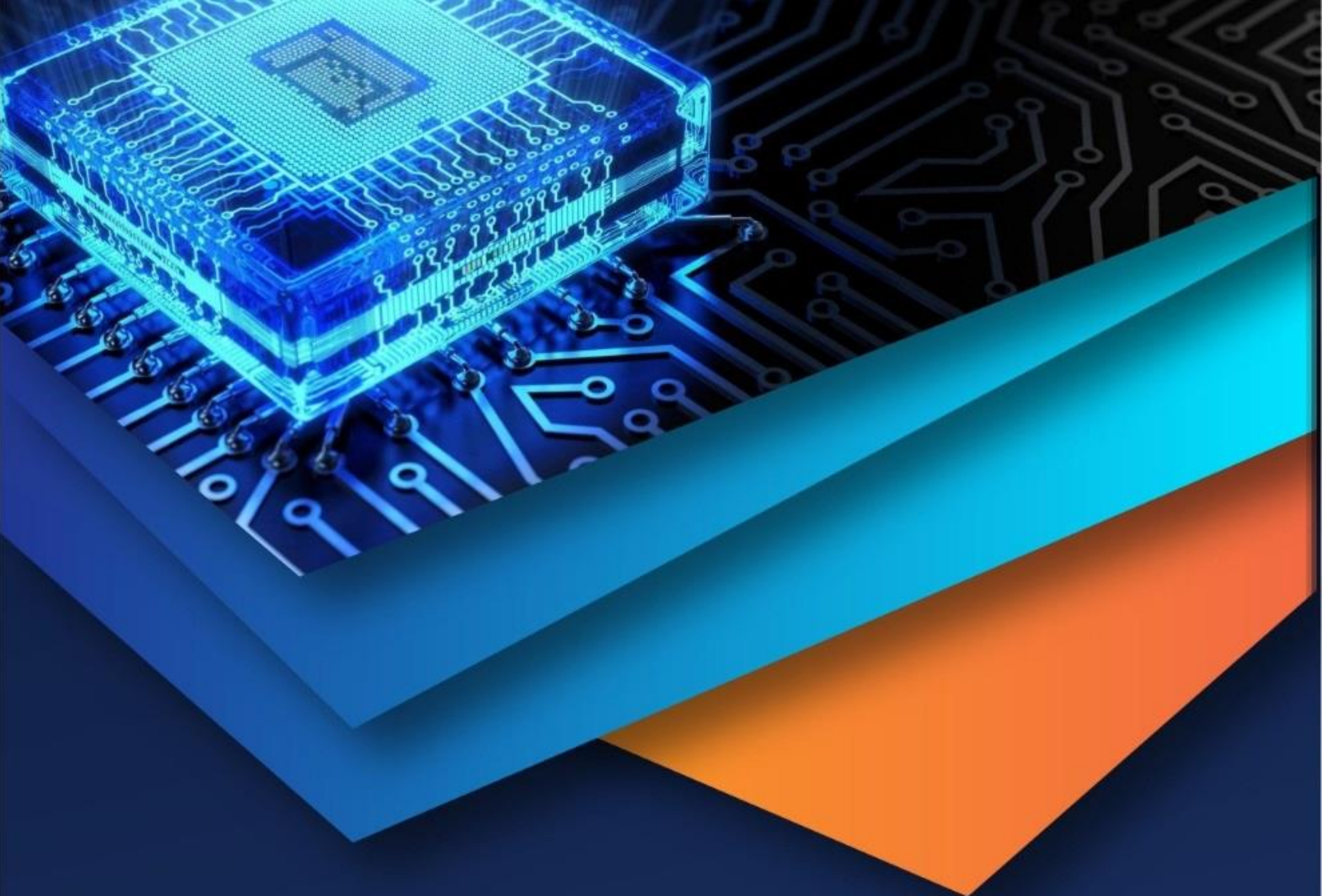

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