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Recent Development of Automotive LiDAR Technology, Industry and Trends

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ABSTRACT

Autonomous driving technology is one of the core technologies for intelligent connected vehicles. For autonomous vehicles with L3 and higher-level capabilities, LiDAR is indispensable. Based on the substantial industry information of the sector and technical development, this paper systematically sorts through and analyzes a variety of LiDAR sensor technologies, the global automotive LiDAR industry ecosystem, major startups, the state-of-the-art products and so on. In addition, this paper provides in-depth research of the automotive LiDAR development trends and judgment on the prospects of automotive LiDAR integrated with the intelligent connectivity industry development trends. This paper considers that the LiDAR sensor has become a bottleneck hindering autonomous vehicles deployment, and predicts the future development paths of automotive LiDAR.

Keywords: autonomous driving; LiDAR; technology paths; solid-state sensor

1. INTRODUCTION

Automotive LiDAR is a kind of radar operating in the optical frequency band that measures distance by using laser (infrared or near-infrared light). It uses a very high sampling frequency through a single transmitter/receiver to generate complete 3D point cloud data [1-3]. LiDAR consists of an optical transmitter, an optical receiver and associated signal processing electronics, as well as a mechanism coordinating the three parts. The combination of different emitter, photodetector, and beam steering technologies provides multiple approaches for designers to realize a LiDAR sensor. LiDAR features such important performance metrics as axial precision, lateral resolution, maximum detection range, field of view, frame rate, transmit power, sensitivity to ambient light and interferers, power consumption, cost and mass production feasibility.

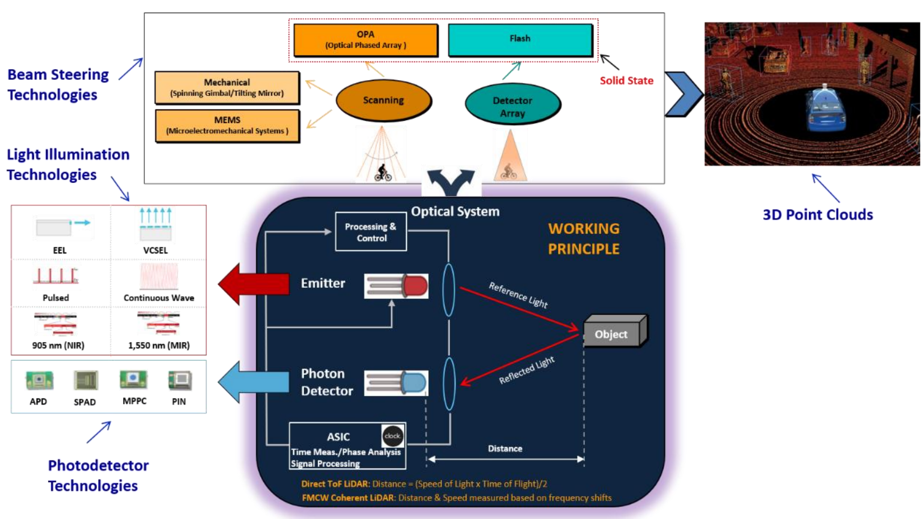

Figure 1. Working principle of LiDAR

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With the advantages of creating high-resolution 3D images, providing medium-range and accurate depth information and identifying targets, LiDAR features wide field of view, high angular resolution, independence on light conditions, and ability to detect lane signs and guideposts. However, LiDAR fails to transmit in rain, snow, fog or dust, and cannot simultaneously meet the requirements for performance, size and cost of mass-produced autonomous vehicles from the layer of industry at present. The typical applications of LiDAR include mapping & navigation, obstacle detection (adaptive cruise control, automatic brake, forward collision warning, parking assistance, cross-traffic alert system), in-cabin monitoring and so on.

In terms of the emitter technologies, automotive LiDAR can be classified into an Edge Emitting Laser (EEL) and a Vertical Cavity Surface Emitting Laser (VCSEL) by light source. An EEL emits light from a small area of the side of the laser die, featuring high performance, high efficiency and high luminance. EELs @ 905 nm are the best fit for cost, efficiency, and output. A VCSEL emits light from surface of the laser die, featuring small footprint, high cost effectiveness, narrow divergence, high efficiency and better temperature tolerance. VCSELs are potentially useful for short-range LiDAR [4]. LiDAR can also be classified into pulsed and continuous wave by photoconduction. The pulsed wave is used for direct time of flight LiDAR, requiring short-pulse emitters & low time-jitter detectors for high precision and resolution and providing longer range. However, peak power is hard to be dealt with for LiDAR-on-chip systems. The continuous wave adopts FMCW or AMCW, which can run with lower power. FMCW linearly-chirped LiDAR measures distance and velocity simultaneously based on beat frequencies using up-down frequency ramps, immune to background light, but requiring more computational power. As for wavelength, it mainly includes 950nm and 1,550nm. The 950nm works with Si-based photon detectors, featuring lower prices and lower loss of light. For eye safety, its power is limited. It is the most commonly used today. Eye insensitive, the 1,550nm allows for higher energy (important in photon budget), less terrestrial solar irradiance but high water absorption, and requires expensive InGaAs infrared (IR) photodetectors[5].

In terms of photodetector technology, the performance requirements of automotive LiDAR photodetectors include high sensitivity, low noise, fast response, wide dynamic range (from very strong to very weak reflected light), wide temperature range, array capability, mass production and low cost. The photodetector technologies mainly include the following four types: the first one is Avalanche Photo Diode (APD), a highly sensitive light-receiving element that provides a built-in first stage of gain through avalanche multiplication. Its signal-to-noise ratio (S/N) can be increased until shot noise limit. APD is used in conjunction with optical bandpass filters to reduce shot noise due to background light, which is suitable for direct ToF, long-range measurement; the second one is Single-Photon Avalanche Diode (SPAD), which is reverse biased like APDs but operates with a bias voltage above breakdown voltage (in Geiger mode). A single photon can set off a significant avalanche of carriers, extremely sensitive, suitable for direct ToF, long-range measurement; the third one is Multi-Pixel Photon Counter (MPPC), as silicon photomultipliers and SPAD-related technology, featuring excellent photon-counting capability and allowing detection of extremely weak light, which is suitable for direct ToF, long-range measurement; the last one is PIN Photodiode, which is a diode with a wide undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region as the most simple light-receiving element, with low cost, stable sensitivity, uniformity and wide dynamic range. It can work under strong background light, which is suitable for direct ToF, short-range and low-voltage measurement [6-7].

In terms of beam steering technologies, automotive LiDAR can be classified into the scanning LiDAR and detector array LiDAR. The scanning LiDAR includes the mechanical scanner (spinning gimbal/tilting mirror), microelectromechanical systems (MEMS) LiDAR, and Optical Phased Array (OPA) LiDAR: For a mechanical scanner, it mounts an array of lasers on a spinning gimbal or rotate a multi-faceted mirror with each facet at a slightly different tilt angle to steer a single beam of pulses in different azimuthal and declinational angles. Velodyne is the representative for such technology. Its advantage lies in 360-degree horizontal FoV, which reuses lens, lasers and detectors across the FoV through rotation, reducing error associated with merging different points of view in real-time. Bulky and expensive, it faces durability issues of moving parts and mass production difficulty. As a semi-solid-state one, MEMS LiDAR uses a tiny microelectro-mechanical systems (MEMS) mirror to electrically steer a beam or beams in a 2D orientation. Usually two mirrors are cascaded to spin in circles and up & down, with much smaller amplitude. The spinning frequency is high enough to prevent mechanical resonances between mirrors and car. With proven technology, compact form and low cost, it can zoom in and out. However, FoV is limited due to confined geometry of mirror constraining oscillation amplitude, and mirrors drift out of alignment over time (especially when there are big temperature changes) [8]. As a true solid-state LiDAR, OPA LiDAR feeds equal-intensity coherent signals to multiple optical antenna elements and achieves beam steering by independently controlling phase and amplitude of re-emitted light by each element, pointing it in a desired direction. Far-field interference produces a desired illumination pattern from a single beam to multiple beams. Reliable and compact, OPA LiDAR features no-moving-parts and lower cost. Light loss in various OPA components makes it hard to achieve a combination of long range, high resolution and wide FoV[9]. As a true solid-state LiDAR as well, Flash LiDAR is a detector array LiDAR. It captures the entire scene with a single light pulse and matches illumination region and FoV of detector (an array of APDs at the focal plane of detection optics). Each APD independently measures ToF to the target feature imaged on that APD with a small size. The resolution is limited by 2D detector pixel size, with low photon budget, limited range (expensive GaAs imagers with high-power IR lights required for longer range) and limited FoV [7,10].

2. THE AUTOMOTIVE LIDAR INDUSTRY ECOSYSTEM

Key participants in the global automotive LiDAR industry ecosystem include illumination sources, photodetectors, optical elements, integrated circuits, and LiDAR system providers. The main illumination source providers include Osram, Hamamatsu, Trilumina, Excelitas and Lumentum. In terms of Photodetector providers, there are Hamamatsu, Philips, Discovery Semiconductors and so on. As for Optical element providers, there are Jabil, Innoluce, Alluxa, VIAVI, Asia Optical and so on. Integrated circuit providers include Texas Instruments, Infineon, Xilinx, Lattice, Cirrus Logic, Wolfson Microelectronics and so on. For LiDAR system providers, there are T1 suppliers such as APTIV and Magna that are getting involved, and other suppliers such as Pioneer, Panasonic, Valeo, Continental, Denso and Ibeo, and startups represented by Velodyne. In general, in addition to the market leader Velodyne, enterprises with different technologies are springing up in the field. Some rising stars are rivaling market leader Velodyne as technology moves toward solid state. OEMs, tech companies and T1 suppliers are also continuously getting involved. T1 suppliers have teamed up with startups, and some already started making their own sensors. Tesla thinks that LiDAR is unnecessary for autonomous driving, and Waymo has its own LiDAR. Except for that, most OEMs are betting on startups directly or through T1s, and some even make multiple bets.

Global automotive LiDAR ecosystem players are springing up. By region, most promising startups are in America, including veteran companies represented by Velodyne as well as young players such as Quanergy, Ouster, Luminar and Argo AI. In addition, significant breakthroughs have been made in Europe, Canada, Israel and Japan. Chinese companies are still at the initial stage of LiDAR production and R&D. In recent years, SureStar, Hesai, Benewake and RoboSense started to enter the emerging automotive LiDAR industry.

LiDAR system providers have different technical orientations by technology. In terms of beam steering technologies, apart from Quanergy's use of OPA LiDAR, most participants are engaged in mechanical scanning LiDAR (including Waymo, Velodyne, Valeo, Ouster, Ibeo, Hesai, RoboSense,etc.), MEMS LiDAR (Valeo, LeddarTech, Innoviz, Luminar, Aeye, Panasonic, Strobe, etc.) or flash LiDAR (Argo AI, Continental, LeddarTech, Oryx Vision); as for emitter technology, the majority of LiDAR system players develop LiDAR based on 905nm pulsed ToF technology[11], except that a few enterprises such as Ouster, Luminar, AEye and Argo AI adopt the emitter technology with the wavelength of 850nm or 1,550nm.

3. KEY LIDAR SENSOR STARTUPS AND THEIR PRODUCTS

3.1 Overseas key players and their products

Overseas key LiDAR players and characteristics of their products are shown in Table 1.

Table 1. Key LiDAR players and characteristics of their products.

LiDAR players	Product characteristics
Velodyne	• Main products include HDL-64E, JDL-32E, VLP(Puck) [12-13] • VLS-128 is the world's most advanced LiDAR sensor at present. It is a rotational, pulsed LiDAR adopting the light source of 905nm wavelength. Compared with HDL-64E, there is 70% size reduction • As a 32-channel non-rotational and semi-solid-state LiDAR, Velarray has the same core sensing engine as VLS-128, smaller size and can be embedded into front/sides/corners of vehicles or integrated in windshield
Ouster	• OS1: first 64-channel LiDAR product, available now with the price only of 12,000 USD • OS-2: range up to 200 meters and the overall size is larger than OS-1 by about 50%[14]

Quanergy	• 905nm, pulsed wave, ToF, OPA and silicon CMOS technologies • S3 was claimed the “World’s First Affordable Solid-State LiDAR Sensor”, while currently being questioned because of short performance needed for general-use autonomous driving[15]
LeddarTech	• pulsed, visible or IR light technologies; light sources are VCSELs or edge-emitting diodes; photodetectors are PINs or APDs; optical components are lenses (for Flash LiDARs) or MEMS micromirrors • provides key components of solid-state LiDAR — signal processing and integrated circuits (SoC chip)
Innoviz	• provide solid-state LiDAR sensors for BMW’s autonomous vehicles which are expected to be launched in 2021 • InnovizOne is an embedded automotive-grade LiDAR applicable to L3-L5 autonomous vehicles. Its FoV increases to 120-degree x 25-degree, the frame rate to 25 fps, and the range to 250 m compared to InnovizPro
Luminar	• single chip, multi-channel, 1,550nm wavelength, pulsed wave and InGaAs photodetector • the highest detection range of 250 meters, 120-degree Horizontal Field of View (two laser beams, each covering 60 degrees) and 30-degree Vertical Field of View
Strobe	• acquired by General Motors in 2017 to combine with its Cruise subsidiary • LiDAR-on-a-chip adopts 1,550nm wavelength, FMCW and PIN photodetector
Argo AI	• GeigerCruizer features 1,550nm wavelength, 1ns pulse, flash, and InP/InGaAs(P) avalanche photodiode • highest detection range is 300 meters (@ 10% reflectivity) and Field of View is 60-degree HFoV x 15-degree VFoV, with about 10 million raw data points per image

3.2 LiDAR Landscape in China

In terms of key players on each link of China’s LiDAR industry chain, there are SINOSEMIC, O-Net Technologies, Accelink and so on as illumination sources providers, China North Industries Group and so on as photodetectors providers, Zhisensor, WIO Tech, Zhejiang Crystal-Optech and so on as optical elements providers, Shenzhen State Microelectronics, GOWIN Semiconductor, ANLOGIC, Sino-Microelectronics, MXTronics and SGMICRO as integrated circuits providers, and SureStar, Hesai, Benewake, RoboSense and so on as representative LiDAR system providers. Generally, short development time of Chinese LiDAR players just and big gap between high-level foreign companies such as Velodyne in multi-channel LiDAR push China to develop towards low-cost products. However, with the maturity of the autonomous driving market and large-scale applications, the market demands need activating.

4. THE STATUS QUO AND CHALLENGES OF LIDAR

4.1 Comparison of Current Products

From the perspective of global LiDAR system players and their various LiDAR products, a complete apple-to-apple comparison is not feasible due to the different technologies/configurations of each product and the limited information disclosed. Nonetheless, a company’s best product to date represents its technical strength and market position. Considering the comparison of each company’s current best product, Velodyne is still leading the mechanical LiDAR market in terms of technical performance. Its 128-channel VLS-128™ is capable of high-speed autonomous driving support. The cost of the product was not disclosed by the Velodyne. Even with a higher power (such as 1,550 nm, and thus more expensive InGaAs photodetector), other types cannot even deliver comparable performance. From the perspective of mass production, currently the Valeo Scala is the only mass-production sensor equipped on the Audi A8 L3 vehicles as of the fourth quarter of 2018, but it’s far from sufficiency for high-speed scenarios.

Table 2. Comparison of each company’s current best product(s).

Company	Current Best product	Technology	Range (m)	HFoV (°)	VFoV (°)	Range Resolution (cm)	H-Angular Resolution (°)	V-Angular Resolution (°)
Velodyne	VLS-128	Mechanical	300	360	40 (+15~-	-	0.11	0.11

		(128CH)			25)			
Ouster	OS-2	Mechanical (64 CH)	200	360	15.8 (+7.9~-7.9)	±3	0.18	0.26
Hesai	40-CH Rotational TOF	Mechanical (40 CH)	200 (@20%)	360	23 (-16~+7)	-	-	0.33
SureStar	32-Line R-Fans	Mechanical (32 CH)	200 (@20%)	360	30	-	0.1	-
RoboSense	RS-LiDAR-32	Mechanical (32CH)	200	360	-	-	-	0.33
Innoviz	InnovizOne	MEMS	250	120	25	3	0.1	0.1
Luminar	Luminar	MEMS (Macro Mirrors,1,550 nm)	250	120	30	-	-	-
Strobe	Strobe	MEMS (1,550 nm)	200 (@10%), 300 (@90%)	-	-	-	-	-
Valeo	SCALA @ Laser Scanner	MEMS	150	145	-	-	0.8	-
Aeye	AE100	MOEMS (1,550nm)	230 (@10%)	70	-	-	-	-
Panasonic	3D LiDAR (for Robots)	MEMS	50	270	60	-	-	-
Argo AI	Argo AI	Flash (1,550 nm) InP / InGaAS(p)	300 (@10%)	60	15	-	-	-
Omron	Long-Range 3D-LiDAR	Flash	150	140	14.4	-	-	-
Benewake	CE30-D	Flash (850nm)	30 (@90%)	60	4	1	0.2	-
Quanergy	S3	OPA	150 (@80%)	120	10	±5	0.1~0.5	0.1~0.5
Velodyne	Velarray	"Frictionless Mechanism" (32CH)	200	120	35	-	-	-
Cepton	Vista	MMT (120 lines)	200	-	-	-	0.2	-

4.2 Major Automakers' Choices

In terms of the choices for LiDAR of major automakers, tech companies and Tier 1 suppliers, T1s are getting prepared—APTIV is betting on all the three major SSL technologies and Valeo has mass produced its own MEMS product for L3 Audi A8. Waymo and GM (through Strobe) in-house develop mechanical scanning and MEMS LiDARs respectively. Mercedes sticks to market leader Velodyne, while BMW turns to Innoviz for MEMS SSL. Ford not only has partnered with Velodyne but also is developing flash SSL with Argo AI. All parties have carried out deployment through independent R&D, cooperation and acquisition, but the development direction is still uncertain.

Table 3. Leading autonomous vehicle developers' current LiDAR choice.

OEM / Tech / T1	LiDAR Partners	Types of Product	OEM / Tech / T1	LiDAR Partners	Types of Product
Waymo	-	Mechanical Scanning	Bosch	TetraVue	Flash + HD Camera

Baidu	Velodyne	Mechanical Scanning (905 nm, ToF) & “frictionless Mechanism” Solid State	Aptiv	Quanergy	OPA, 905nm
GM	Strobe	MEMS,1550 nm, FMCW		Leddartech	Flash & MEMS
Ford	Velodyne	Mechanical Scanning (905 nm, ToF) & “frictionless Mechanism” Solid State		Innoviz	MEMS, 905nm
	Argo AI	Geiger-mode Flash, 1,550 nm	Valeo	Leddartech	Flash & MEMS
Daimler	Velodyne	Mechanical Scanning (905 nm, ToF) & “frictionless Mechanism” Solid State		Ibeo	Scanning & Unknown Solid State
BMW	Innoviz	MEMS, 905 nm	Magna	Innoviz	MEMS, 905nm
Audi	Valeo	MEMS, 905 nm	Continental	ASC	Flash
Volkswagen	Velodyne	Mechanical Scanning (905 nm, ToF) & “frictionless Mechanism” Solid State	Denso	TriLumina	Flash, 940 nm VCSEL Arrays
Volvo	Velodyne	Mechanical Scanning (905 nm, ToF) & “frictionless Mechanism” Solid State	ZF	Ibeo	Scanning & Unknown Solid State
	Luminar	MEMS, 1,550 nm			
Toyota	Luminar	MEMS, 1,550 nm			
Jaguar	Quanergy	OPA, 905 nm			
Nissan	Quanergy	OPA, 905 nm			
Hyundai	Quanergy	OPA, 905 nm			

4.3 Technical Path Choices

Back to technical path choice, the mechanical scanning LiDAR can provide 360-degree FoV and excellent ranges with enough channels. But there are multiple challenges that are hard to overcome: the first one is huge size. The mechanical scanning LiDAR is usually roof-mounted rather than embedded. The second is high price. Products with ranges of more than 200 meters are priced at least $25,000 piece per piece. The third is mass production difficulty. The fourth is the durability problem, which is associated with moving parts, especially due to vibration, shock, wear and tear, cleaning and so on. Because of these reasons, the size and cost of LiDAR must be reduced, which naturally leads to the development of solid-state technology [11], while semi-solid state is expected to be the intermediate state before the final transition to the solid state and the launch into the autonomous driving market more quickly.

As a semi-solid-state LiDAR, MEMS LiDAR is chip-based, more compact and less costly with good performance, so it may fill the gap in the market and achieve fully autonomous driving capability more quickly. However, there are also some problems such as limited range (tiny mirrors limit reflected light), restricted FoV (low oscillation amplitude translates into limited field of view) and drift out of alignment (mirrors don’t maintain calibration and may need recalibrated over the lifetime when there are big changes in temperature).

In terms of solid-state LiDAR, optical phased array (OPA) LiDAR has no moving parts, so it is more compact and cheaper. Beam divergence — light loss in the various OPA components is more than any other techniques. Performance compromise — it is hard to achieve a combination of long range, high resolution and wide FoV, and still at the early stage of development now. Flash LiDAR avoids complexities due to object or LiDAR movement by capturing entire scene in a single instant. The problem is energy inefficiency. Light from each flash is spread over entire FoV, so only a fraction strikes any particular point. Limited range, resolution, and FoV (low photon budget makes each pixel in detector array necessarily quite small, limiting the amount of returned light it can capture and detection resolution.)

For any type, a 1,550nm laser (invisible wavelength, eye-safe) allows for the use of significantly higher powers (thus better performance); but low-cost silicon photodetectors cannot “read” blasts of light in that spectrum, and more expensive gallium-arsenide detectors are required. It also causes other issues such as water absorption. In addition, LiDAR itself has intrinsic weaknesses — failure to distinguish color, to tell the color of traffic lights, and need complementary color cameras). LiDAR is not well-suited for speed tracking compared to radar. In addition, LiDAR is hard to deal with edge cases such as bright sun against a white background, blizzard-caused whiteout conditions, heavy rain, snow, fog, dust, remote black objects and so on. Therefore, in addition to LiDAR, the fusion with sensors based on different technologies is critical for autonomous driving to provide redundancy and reliable perception [16-17].

5. CONCLUSION

With its high resolution and superb depth information provided, LiDAR technology is commonly agreed to be a key enabler of autonomous driving. It allows the vehicle to generate huge 3D maps and then navigate predictably within; in the meantime, detect and track objects along the way. Through extensive collection and systematical analysis of massive information related to the LiDAR industry and technology development, this paper provides an in-depth study of the working principle, industry ecosystem, major startups and their products and status quo of development.

According to the research, despite the continuous budding of startups around the world, there is not yet a single sensor that can be mass-produced for automotive grade with reasonable cost while meeting the performance requirements for higher-level automations. Therefore, LiDAR sensor has become a bottleneck of high-speed self-driving vehicles deployment.

Facing such a problem, this paper provides such projections for LiDAR development paths in the future based on comprehensive analysis: Some initial Robo-taxis may still use mechanical scanning LiDAR sensors thanks to their unbeatable performances, because savings from removing human-drivers help offset some sensor cost and operating a fleet of vehicles can amortize costs over years of service. In addition, the roof-mounted spinning “coffee can” won’t bother ride-sharing passengers too much; the premium private-ownership market could also tolerate the cost; but for the volume market, low-end solid-state sensors are expected. Multiple (and perhaps different types of) LiDAR sensors will be needed depending on the objectives (for long range, high resolution, or wide field of view), MEMS LiDAR sensors could be a good choice for transition. Finally, since experimental and low-volume hardware for cutting-edge technology (including LiDAR) is almost always expensive, hopefully LiDAR sensors will eventually become cheaper through the process of mass manufacturing and iterative improvements, which will further propel the comprehensive transformation of the automotive industry and even social mobility [18].

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