An Overview on LiDAR for Autonomous Vehicles.

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***Abstract*—Automotive Light Detection and Ranging (LiDAR) plays an important role in precisely identifying and detecting road conditions and is crucial for the adoption of Advanced Driver Assistance Systems (ADAS). Their designs and scanning techniques can impact the vehicle's performance and navigation. This makes the choice of the right LiDAR for the specified application extremely important. However, as the technologies improve, automotive LiDAR sensors are still evolving. This paper provides an overview of LiDAR by Introducing the sensor and its basic working principle and examining the various imaging systems along with their advantages and limitations. Subsequently, a comparative study of various Velodyne sensors is discussed.**

***Keywords*—LiDAR, autonomous vehicles, ADAS, automotive sensors, Velodyne, imaging systems, laser beams, 3D mapping, road safety, sensor technology, Velodyne sensors comparison, rotor-based mechanical LiDAR, solid-state LiDAR, MEMS technology, optical phased array, flash LiDAR, comparative study, vehicle surroundings, distance calculation formula.**

I. Introduction

On average, at least one person is killed in road accidents every minute in the world. Car crashes kill thousands of people and leave nearly a million people severely injured [1]. Advanced driver assistance systems (ADAS) are being used to assist drivers in such situations. An autonomous car also known as a self-driving car, can sense its surrounding using ADAS and a variety of sensors(RADAR, optical image, LIDAR, GPS, wheel speed, and vehicle communication systems) [2]. Light Detection and Ranging(LiDAR), is one of the most significant automotive sensors. LiDAR uses laser beams to visualize the area around it. LiDAR creates a three-dimensional map of the environment and this allows the autonomous car to navigate safely. Additionally, LiDAR can detect objects even in low-light conditions, making it an optimal sensor for driving at night or in adverse weather conditions. It uses the method of laser-illuminating the target and measuring the reflected light to ascertain the variation in the reflected light in terms of wavelength and arrival time. It is employed to create a perspective of the vicinity of the car, which could contain pedestrians and other moving things. [3]The reflectivity of an object—the quantity of reflected light or radiation it produces—determines the x, y, and z coordinates, timing, and intensity of the data points that LiDAR gives. It is employed to create a perspective of the vicinity of the car, which could contain pedestrians and other moving things [4].

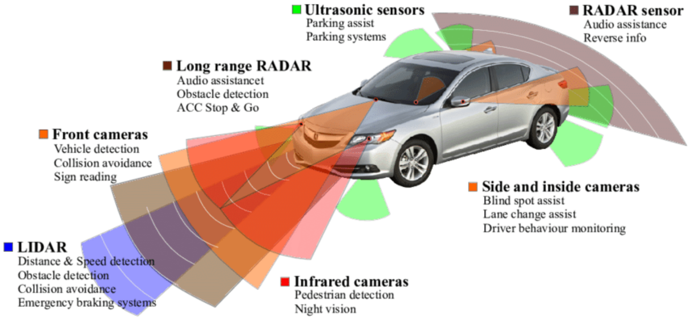

Fig. 1. LiDAR and other typical types of Sensors in ADAS [9]

Fig. 1 depicts a setup using typical types of sensor technologies used in ADAS. The LiDAR sensor is used to translate the real world into 3D digital images in real-time and with a high level of confidence, while cameras can aid in features like object detection, classification, and collision avoidance. The radar aids in cross-traffic alerts, blind-spot assistance, and adaptive cruise control [6].

The use of LIDAR for automotive purposes dates back to the Defense Advanced Research Projects Agency's (DARPA) Autonomous Vehicle Grand Challenges of 2004–2007 [5] [6], though it was used in other domains previously[8][10]. Even though none of the competitors succeeded in the challenge, it became almost essential to have a real-time obstacle avoidance system with LiDAR-based sensors. Five vehicles completed the challenge in the second round, with Stanley being the first to reach 244 km in seven hours[5]. More than a decade after the first autonomous ride, we can state that we are now moving forward to putting fully autonomous vehicles on our roads. As a result of recent developments in sensor technology and onboard computing power, a variety of sensors may now be installed on vehicles to collect a lot of data in real-time which can conquer challenges such as vehicle indoor simultaneous localization and mapping (SLAM), autonomous navigation and obstacle detection.[6][7] This paper is a brief about the working principle of LiDAR, various imaging systems used to visualize a vehicle's surroundings, and a comparative study between various types of Velodyne sensors considering various important parameters.

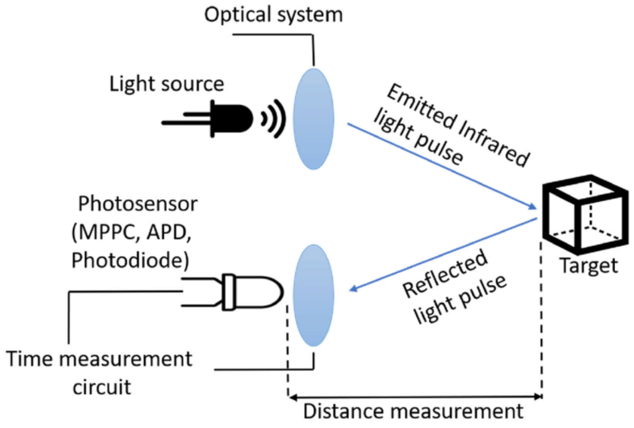

Fig. 2. LiDAR and time of flight ToF principle Adapted from [8].

II. BASIC PRINCIPLE

The LiDAR system consists of four basic parts; a transmitter, a receiver, an optical analysis device, and a powerful computer [4]. The transmitter of the LiDAR emits laser pulses to its surroundings. The reflected light or pulsed echo from the target object is detected by the system receiver. Phase shift, pulse width, pulse power, and round-trip time are often utilized parameters when analyzing light signals. The point cloud that represents such information in 3D or, in some configurations, in 2D is generated using the reflections that have been captured from the object. In addition, an optical analyzing system is used to process the obtained input data, and a computer helps to visualize precise and high-quality live images of the system's surroundings. The design concept of LiDAR is based on the idea of the reflection of light based on the Time-of-flight ToF principle as depicted in Fig.2. The LiDAR system adhering to the ToF principle fires laser beams onto the surface and measures the time taken for the reflected light to reach the sensor. This process is repeated until a detailed map of the surface is generated. Due to how swiftly light travels, LiDAR can calculate the precise distance very quickly and produce the digital representation of the target. The distance calculation formula is found in the equation:

$$D = c(\Delta T/2) \tag{1}$$

The distance(D) from the LiDAR sensor to the target is calculated by dividing the time difference (ΔT) by 2 and multiplying it by the speed of light (c). [11] Equation (3) describes the relationship between the emitted power Ps and received power Pr of LiDAR systems. The main variables in Equation (2) are listed in Table 1. 15

$$P_r = \frac{P_s \cdot T_A \cdot \eta_t}{A_s} \cdot \frac{\Gamma_\rho \cdot T_A}{\pi r^2} \cdot \frac{A_R \cdot \eta_r}{1} \tag{2}$$

TABLE I
VARIABLES IN EQUATION (2)

Symbol	Quantity	Units
P_r	Received power	W
P_s	Emitted power	W
T_A	Atmospheric transmission	-
η_t	Optical efficiency of the emitter	-
A_s	Beam spread area of the emitter at the target	m^2
Γ	Target cross-section	m^2
ρ	Reflectance of the target	-
r	Distance between LiDAR and the target	m
A_R	Optical aperture of the receiver	m^2
η_r	Optical efficiency of the receiver	-

III. LIDAR IMAGING SYSTEMS

To recreate a vehicle's surroundings, various imaging architectures can be utilized through the measuring methods discussed. LiDAR systems can be classified into three types: (1) beam steering sensors that scan the entire environment using a rotor-based mechanical part [18]; (2) solid-state beam steering sensors that don't require bulky spinning mechanical components; and (3) full solid-state sensors with no mechanical parts that move [17].

A. *ROTOR-BASED MECHANICAL LIDAR*

The automotive industry currently relies on rotor-based mechanical LiDAR sensors for imaging, with this being the most established technique [16]. These sensors are widely used in driverless systems and can offer a 360○ view horizontally, with varying ranges vertically. The sensor achieves a 3D 360○ horizontal view through a mechanical rotation system, while the vertical view is determined by the number of emitter/receptor pairs, also known as channels. However, this type of sensor has some drawbacks, including its bulky rotating part, which adds inertia to the system, as well as overall power consumption and weight. Compared to other LiDAR sensor technologies, rotor-based systems are more expensive, even among companies such as Velodyne, Hesai, Ouster, Quanergy, and Robosense, which have all pioneered this method.

B. *SCANNING SOLID STATE LIDAR*

Solid-state LiDAR systems or LiDAR systems without spinning mechanical components, are less expensive due to their constrained field of view. But a wider field of view is created in the automotive industry by combining several sensor outputs with the surroundings of the vehicle. This LiDAR imaging system has brought in new technologies, such as microelectromechanical (MEMS) and optical phased array (OPA) systems.

1) Microelectromechanical systems (MEMS): Mirror MEMS solutions use MEMS technology to replace external rotating parts with tiny electromechanical mirrors whose tilt angle varies when applying a stimulus such as a voltage. The MEMS system is a substitute for mechanical scanning hardware with an electromechanical equivalent.[18] Instead of moving the laser position mechanically across the field of view, this method utilizes a stationary laser that directs toward electromechanical mirrors. Through the application of a pull-in voltage, these mirrors are capable of adjusting their tilt angle. It is important to note that aware that the continuous vibrations and shocks experienced in a moving vehicle can affect the functionality of MEMS mirrors, which are categorized as resonant or non-resonant.[20]. To enable 3D scanning, 2D MEMS laser projectors can be used with either a single mirror that has two oscillation axes or with two separate mirrors, one for each axis. The second option is better at withstanding vibrations and has a simple design, making it easier to create. However, the first option has benefits for packaging and aligning the axis, resulting in a more accurate sensor. In cars, the mirror that controls the horizontal axis moves faster and has frequencies ranging from 0.5 to 2kHz. The mirror controlling the vertical axis moves at a slower pace and operates at frequencies between 10 and 30 Hz. Additionally, MEMS-based systems have a limited field of view ranging from 25○ to 150○ and a shorter range compared to mechanical rotor-based sensors. The power emitted by the MEMS mirror needs to be decreased to prevent any damage to its delicate parts. Multiple companies offer MEMS-based LiDAR sensors, such as Blickfeld, Innoviz, RoboSense, and ZVISION. High resonant frequency MEMS mirror is generally preferred because it can scan fast, reach high resolutions provide high frame rates, and higher resonant frequency that leads to greater robustness. The resonant frequency(f0) of a MEMS mirror is given by:

$$f0 = 1/2\pi(km)^{1/2} \tag{3}$$

where m is the equivalent mass and k is the equivalent spring constant of the MEMS mirror. [13].

2) Optical Phased Array Scanner: OPA systems use phase modulators to steer laser beams, similar to how phased array Radar works. The modulator can change the shape of a signal by controlling when a beam passes through a lens. This allows for the emission of light to be controlled in a specific direction by adjusting the phases of a group of laser emitters, To eliminate unwanted signals and reduce multi-path reflection phenomena, the sensor only collects light from the illuminated spot. Using OPA-based technology, the receiver can similarly control the receiving light [12] [19].

C. FULL SOLID STATE LIDAR

Flash LiDAR systems are considered solid-state because they do not have any rotating parts. They work like digital cameras by using a flashlight to illuminate the environment and photodetectors to collect the backscattered light. This method allows for faster data capture and is highly resistant to light distortion. But the receiver must be able to differentiate the returning light from each point, which can be expensive due to the photodetector arrays used to define the sensor's spatial resolution. Flash LiDAR sensors require more power to illuminate the entire field of view, limiting their detection range to between 50 and 100 meters. They are typically used for blind-spot detection of large objects like cars and pedestrians. While they are simpler in terms of mechanical and optical systems, they require more sophisticated electronic components. Manufacturers that offer flash-based LiDAR sensors include ASC, LeddarTech, Ouster, Sense Photonics, and Xenomatics [12] [19].

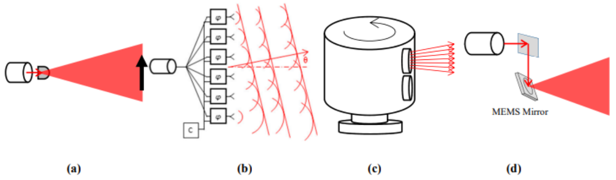

Fig. 3. (a) A flash LiDAR with diffused light; (b) The principle of an optical phased array (OPA) scanner; (c) A LiDAR motorized spinning scanner; (d) A microelectromechanical systems (MEMS) laser scanner. [13]

Fig. 4. Different Velodyne Sensors [19]

IV. COMPARATIVE STUDY BETWEEN VARIOUS VELODYNE SENSORS

Different Velodyne LiDAR sensors have been available in the market. With time, they have significantly contributed to the development of autonomous technologies. Veldoyne offers a variety of LiDARs for various purposes. Velodyne LiDAR, the leading innovator in the LiDAR industry, provides a wide range of LiDAR sensors that cater to various needs and applications. This comparison will cover seven notable sensors offered by Velodyne: HDL-32E, VLP-16, Puck, Ultra Puck, Alpha Prime, Alpha Prime 360, and Velarray. Each sensor has unique strengths, including compact designs and advanced perception capabilities. [19]

- Resolution: The Alpha Prime stands out with its high-resolution point cloud data, capturing fine details of the surroundings. The HDL-64E and HDL-32E also offer high-resolution capabilities, while the Puck Hi-Res provide enhanced resolution compared to the standard Puck and Puck Lite models.
- Field of View (FoV): The HDL-64E provides an expansive 360-degree horizontal FoV and a 26.8-degree vertical FoV. The HDL-32E offers a 40-degree vertical FoV, while the VLP-16, Puck, Puck Lite, Puck Hi-Res, Ultra Puck, and Alpha Prime provide a 30-degree vertical FoV.
- Range: The HDL-64E, HDL-32E, Puck, Puck Lite, and Alpha Prime have a maximum range of 100 meters. The

VLP-16 has a range of up to 100 meters, while the Ultra Puck offers a shorter range of 75 meters.

- Accuracy: Velodyne sensors, including the HDL-64E, and HDL-32E have an accuracy of 2cm whereas Puck, and Alpha Prime, are known for providing a high accuracy of 3cm.
- Scan Rate: The HDL-64E sensor has a scan rate of around 1.3 million points per second(pps), while the HDL-32E has a scan rate of 700,000 apps. The VLP-16, Puck, Puck Lite, Puck Hi-Res, Ultra Puck, and Alpha Prime have comparatively lower scan rates of 300,000 pps.
- Data Interface: All sensors offer Ethernet as the data interface, providing convenient connectivity and compatibility with various systems.
- Power and Voltage: Specific power and voltage details may vary, but these sensors generally operate within the range of 8.5-10 watts of power consumption and 9-16 volts of voltage input.
- Size and Weight: The HDL-64E and HDL-32E are larger and heavier sensors, designed for robust applications. The VLP-16, Puck, Puck Lite, Puck Hi-Res, Ultra Puck, and Alpha Prime offer compact and lightweight form factors, suitable for applications with space constraints. [19]

These sensors have their own features and performance zones, depending on which they can be chosen for required applications. For example, The HDL-64E is best suitable for applications requiring detailed 3D mapping and long-distance perception suitable for applications requiring detailed 3D mapping and long-distance perception due to its high-resolution and extensive range while The Alpha Prime provides high-performance and advanced features with extended range, high resolution, and reliability. It is often selected for applications in autonomous vehicles, robotics, mapping, and research that require the utmost precision, accuracy, and performance.

V. VISUALIZATION AND ANALYSIS OF RESEARCH LANDSCAPE

In this section, I present the network visualization generated using VOSviewer. The network illustrates the relationships and connections between different concepts, keywords, or topics within the field of Automotive LiDAR. Each node represents a distinct term, while the links between nodes indicate co-occurrence or co-citation patterns.

1) Density Map:

- **Density Map Overview:**
  - The image under Fig.5 represents a visual summary of terms and topics frequently associated with Automotive LiDAR research.
  - Each term is displayed in varying shades of green and blue, indicating its density or frequency of occurrence within the field.
- **Central Term: ”LiDAR”:**
  - The central term prominently displayed is ”LiDAR”, which stands for Light Detection and Ranging.

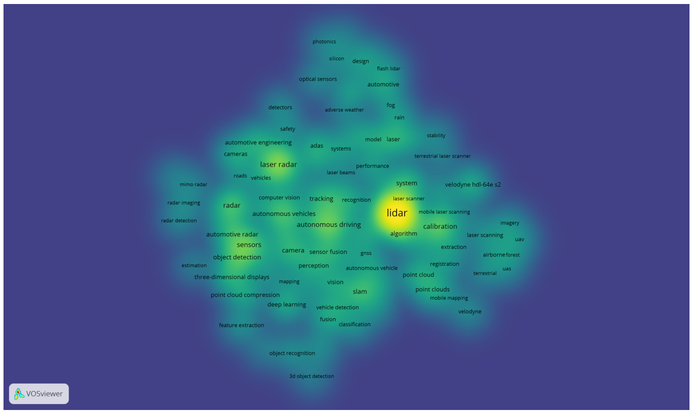

Fig. 5. Density Map

  - LiDAR technology plays a crucial role in automotive applications, particularly in the development of autonomous vehicles and advanced driver assistance systems (ADAS).
  - It involves using laser or light pulses to measure distances and create detailed 3D maps of the environment.
- **Surrounding Terms:**
  - Encircling the central term are related terms that contribute to the broader understanding of Automotive LiDAR:
    - ”Autonomous Vehicles”: Refers to self-driving cars and trucks that rely on LiDAR sensors for navigation and obstacle detection.
    - ”Object Detection”: The process of identifying and locating objects (such as pedestrians, vehicles, or obstacles) using LiDAR data.
    - ”Radar”: Another sensor technology used in automotive applications for detecting objects and measuring their speed.
    - ”Laser Radar”: A synonym for LiDAR, emphasizing its role in radar-like sensing.
    - Other terms may include ”Mapping”, ”Environment Perception”, and ”Sensor Fusion”.
- **Significance and Interconnections:**
  - The arrangement of terms suggests their interconnectedness and relevance within the field.
  - Researchers studying Automotive LiDAR likely explore these topics in-depth, aiming to enhance safety, efficiency, and performance in autonomous vehicles.
- **Research Implications:**
  - The density map provides insights into the current state of research, highlighting areas of focus and potential gaps.
  - Scholars can use this visualization to identify emerging trends, collaborative networks, and key research directions.

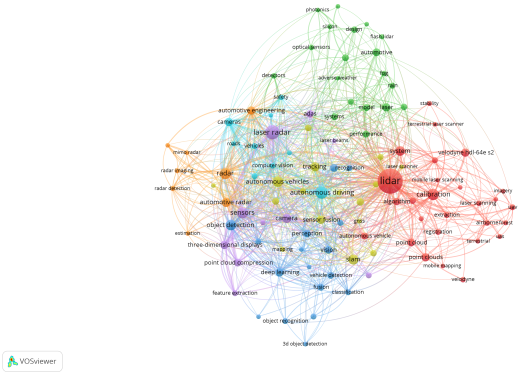

Fig. 6. Density Map

A. Network Visualisation

- **Network Structure:**
  - The Fig.6 depicts a semantic map or network of interconnected terms specifically related to Automotive LiDAR technology and data analysis. Each term (or node) is connected to others through lines of varying colors, indicating different types or levels of relationships. The nodes are color-coded and clustered to represent their close associations within the Automotive LiDAR domain.
- **Key Terms and Relationships:**
  - Prominent terms in the network include:
    - **"LiDAR"**: Likely associated with technology related to light detection and ranging, particularly in the context of automotive applications.
    - **"Autonomous Vehicles"**: Refers to self-driving cars and their LiDAR-based technology for navigation and obstacle detection.
    - **"Data Processing"**: Indicates the handling and analysis of large LiDAR datasets generated by automotive sensors.
  - The lines connecting these terms suggest their interdependencies or shared contexts within the Automotive LiDAR field.
- **Complexity and Intersections:**
  - The image visually represents the complex relationships and intersections between Automotive LiDAR concepts. It captures the intricate web of knowledge and how different terms specific to Automotive LiDAR are linked within the field.

The generated images offer valuable insights into research domains, showcasing relationships, trends, and key concepts. Density maps reveal term frequency and distribution, guiding researchers to relevant topics. Network graphs display interconnected concepts, highlighting clusters and central nodes. These visualizations help researchers navigate scholarly information, spot trends, and identify collaborative networks, aiding informed decision-making and research advancements.

VI. SUMMARY

The report presented the Light Detection and Ranging (LiDAR) Sensor and its applications as an automotive sensor in the autonomous driving vehicle industry. The working principle and the various LiDAR imaging systems namely the solid and mechanical LiDARS bring to sight the requirements, varieties, and possible choices in LiDAR depending on the application and requirement for an application. The comparative study between various Velodyne sensors from the pioneering company in the field of LiDARS shows the differences between LiDARS and the improvements in various parameters with time to meet new requirements and overcome previous limitations. Choosing the right imaging method, adhering to the requirements, and selecting the right sensor for the application can obtain accurate and precise results specifically for ADAS, assisting drivers to overcome the limitations and boundaries of mechanical driving. In the comparison, the VLP 16 showed a cost-effective performance with a satisfactory range for urban driving scenarios. The HDL-32E demonstrated enhanced capabilities, such as a greater field of view, increased range, and increased resolution, which made it suited for navigating challenging areas. The Alpha Prime came out on top, offering great range, resolution, and field of view, despite being more expensive. Exciting times lie ahead as we witness the continued evolution of imaging systems, paving the way for a future where autonomous vehicles become a common reality, transforming the way we travel and shaping the world of transportation.

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