

Lidar Sensor Technology

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Abstract

LiDAR, or Light Detection and Ranging, is a laser-based remote sensing technology that uses laser beams to measure distances and detect movement within an environment in real time. This paper presents an exploration of LiDAR technology, its principles, hardware components, and architecture. Next, we examine current challenges, such as environmental limitations, data-processing demands, and strategic debates over sensor adoption especially Tesla's strategic avoidance of LiDAR, before discussing its integration with other sensing technologies like cameras, radar, etc. Applications in unmanned aerial vehicles (UAV) are also presented to illustrate LiDAR's impact on autonomous navigation and mapping. Finally, the paper sets LiDAR within the broader industry and market trends and explores its role in enabling spatial computing.

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Introduction

Light Detection and Ranging (LiDAR) is an active remote sensing method that emits laser pulses to measure time-of-flight (ToF), creating 3D spatial representations known as point clouds (Bogue, 2022). Modern LiDAR systems offer precise measurement irrespective of lighting conditions, which makes them invaluable in autonomous vehicles, UAVs, and even archaeology. As LiDAR systems become smaller and more affordable, they could be integrated into drones and other small devices, enabling fast and real-time observation in non-GPS and low-light environments ideal for UAV-based applications like obstacle avoidance (Merei et al., 2025). LiDAR is one of the foundations of spatial computing with real-time environment for tasks like localization, and mapping.

LiDAR System Components

A LiDAR system includes four main components: a laser emitter, a scanning mechanism, a photodetector (receiver), and timing and processing electronics. These components work together to produce light pulses, detect reflections, and process spatial information in order to create 3D representations of environments (Seidaliyeva et al., 2025; Lukashchuk et al., 2023).

Laser Emitter

To balance atmospheric transmission efficiency and eye safety, LiDAR systems generally use near-infrared (NIR) laser wavelengths of 905 nm or 1,550 nm.

Scanning Mechanism

The LiDAR system's scanning mechanism controls how it scans its surroundings to collect spatial data.

Photodetector (Receiver)

The photodetector captures the reflected light from targets and converts it into electrical signals for time-of-flight (ToF) calculation. Several photodetector technologies are used depending on the wavelength and sensitivity requirements.

Timing and Processing Electronics

Precise timing is essential for accurate ToF measurements. Return pulse delays are measured with nanosecond accuracy using devices such as time-to-digital converters (TDCs) and digital delay generators. These delays are translated into range values by embedded processors or external computing units.

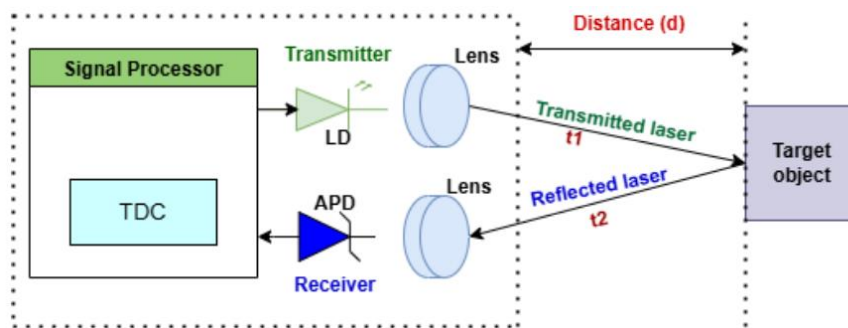


Figure 1: Structure of a LiDAR Sensor

Working Principle of LiDAR

LiDAR operates based on two main measurement methods: Time-of-Flight (ToF) and Frequency-Modulated Continuous-Wave (FMCW). While both techniques measure distance, FMCW also provides velocity information (Kong, 2025).

Time of Flight (ToF) LiDAR

ToF LiDAR measures the time it takes for a laser pulse to travel to an object and return. Distance d to the target object is computed using the following equation:

$$d = \frac{c \cdot t}{2}$$

where c is a constant value of the speed of light and t is the time of flight between the transmitted pulse and the reflected echo (Seidaliyeva et al., 2025).

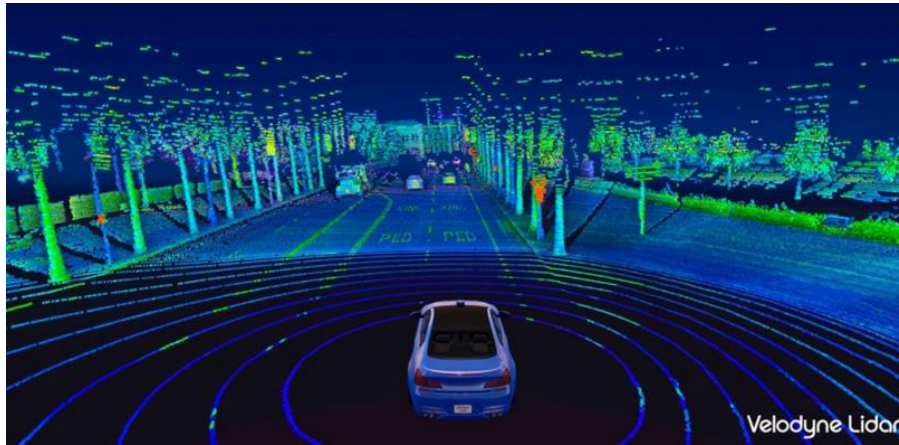


Figure 2:A point cloud created by ToF Lidar

Frequency-Modulated Continuous-Wave (FMCW) LiDAR

FMCW LiDAR releases a laser beam whose frequency varies over time. Reflected signals are compared with a local reference beam to determine both distance (via beat frequency) and relative velocity (via Doppler shift).

Advantages:

- Greater dynamic range: Can handle higher optical power without blooming which usually occurs when a sensor receives an overwhelming reflection from a bright object (Kong, 2025).
- Velocity measurement: Extracts Doppler shift directly, effective for object tracking

Challenges:

- Complexity and cost: Requires coherent lasers and accurate analog/digital hardware (Seidaliyeva et al., 2025)

Types of LiDAR

LiDAR systems can be classified by their scanning methods, laser modulation, and hardware architecture. Below are the main LiDAR types (Royo & Ballesta-Garcia, 2019, Behroozpour et al., 2017):

Mechanical Spinning LiDAR

Mechanical LiDAR uses rotating assemblies, either the entire sensor or a spinning mirror to scan a full 360° horizontal field of view. This approach has dominated early automotive and robotics deployments.

Advantage:

- Wide field of view

Limitations:

- Bulky and heavy
- Moving parts limit reliability and lifespan
- Higher power consumption

MEMS Scanning LiDAR

MEMS (Micro-Electro-Mechanical Systems) LiDAR uses micro mirrors to deflect the laser beam across the scene. This architecture enables solid-state scanning, reducing moving parts and improving durability.

Advantages:

- Small form factor
- Low cost in volume
- Fast scanning rates

Limitations:

- Limited field of view compared to mechanical units

MEMS LiDAR is increasingly adopted in drones due to its balance of size, performance, and cost.

Flash LiDAR

Flash LiDAR emits a broad, simultaneous illumination pulse and captures the entire scene using a 2D detector array (similar to a camera sensor).

Advantages:

- No moving parts
- Compact and lightweight

Limitations:

- Limited range compared to scanning systems
- Lower angular resolution

Flash LiDAR is commonly used in small UAVs, robotics, and augmented reality where size and simplicity are critical.

Frequency-Modulated Continuous-Wave (FMCW) LiDAR

FMCW LiDAR combines distance and velocity measurement. It transmits a continuously chirped laser signal and measures beat frequency to infer range and Doppler shift for speed.

Advantages:

- Simultaneous range and velocity data
- High dynamic range

Limitations:

- Greater system complexity
- Currently higher cost and integration challenges

FMCW is increasingly seen as the future of automotive and drone perception, with several companies announcing chip-scale prototypes.

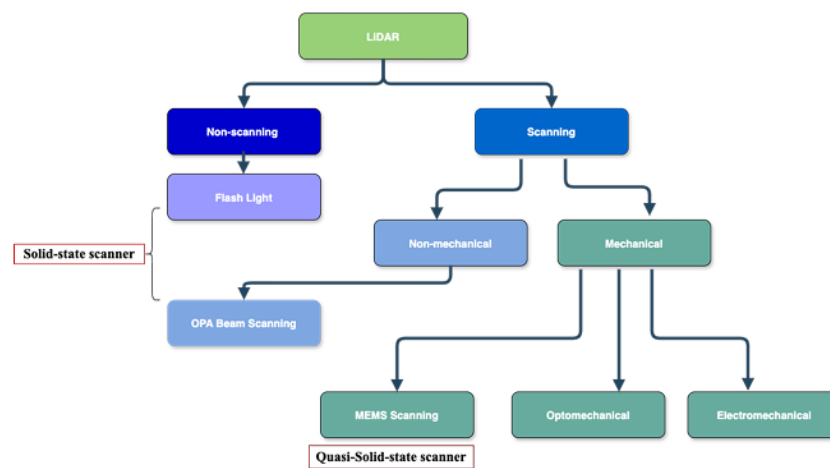


Figure 3: Different types of LiDAR Sensors

Challenges and Issues in LiDAR Technology

While LiDAR offers unmatched 3D sensing capabilities, it has several technical, economic, and philosophical disadvantages. This section discusses the main limitations, specifically the current debate in autonomous driving represented by Tesla's decision to avoid LiDAR.

Technical Challenges

- LiDAR units often require high-power lasers, cooling, and precision optics. In drones and electric vehicles, these elements have a direct effect on battery life and operational range (Bogue, 2022).

- Although prices have fallen in the last ten years, high-performance LiDAR (such as FMCW or long-range solid-state) remains more expensive than radar or camera-based alternatives.
- LiDAR performance degrades in fog, heavy rain, snow, or dust.

Philosophical and Strategic Debates: The Tesla Perspective

Tesla has chosen vision-only autonomy over LiDAR. Elon Musk, the CEO, has frequently referred to LiDAR as "a crutch" and "a fool's errand", arguing that real-world AI must solve perception with the same inputs as humans, mainly cameras (Hawkins, 2021).

Tesla's Justification:

- According to Tesla, cameras can provide enough spatial information when combined with neural networks, and LiDAR simply duplicates information expensively.
- The cost of every vehicle would increase if equipped with high quality LiDAR.
- For millions of vehicles, moving parts in mechanical LiDAR create durability issues.

LiDAR Integration with other sensing technologies

While LiDAR offers depth perception, combining it with other sensors improves its performance. This sensor fusion approach is essential to advanced autonomous systems, spatial computing platforms, and robotics.

Motivation for Sensor Fusion

Single-sensor limitations drive the need for integration:

- LiDAR has trouble with some weather conditions (such as fog and rain) and surfaces (such as transparent glass).
- Although cameras offer detailed visual information, they struggle with change in lighting variability and cannot accurately measure depth.

- Radar performs well in different weather conditions such as fog and rain but lacks fine spatial resolution.

By combining sensors, systems can balance weaknesses and make the most of each sensor's strengths.

Typical Multi-Sensor Configurations

LiDAR + Cameras

- Use case: Object detection, classification, and mapping
- How it works: Cameras provide colors and textures, while LiDAR provides depth information

LiDAR + Radar

- Use case: All-weather navigation and obstacle detection
- How it works: LiDAR gives clear shape details, while radar still works well when visibility is low

Benefits of Integration

- Robustness: Maintains perception in different conditions
- Redundancy: Improves safety by reducing dependence on only single sensor

LiDAR in UAV Applications

This section discusses how LiDAR supports autonomous operations, mapping, and obstacle avoidance in drones (Liu et al., 2025).

Terrain Mapping and 3D Reconstruction

LiDAR-equipped drones can scan large areas and create detailed 3D maps and elevation models. This is widely used in:

- Environmental monitoring
- Agriculture
- Infrastructure inspection
- Archaeology

Obstacle Detection and Avoidance

For autonomous navigation, LiDAR provides:

- Obstacle detection: Real-time point cloud generation enables detection of static and dynamic obstacles
- Collision avoidance: Drones use LiDAR data to change direction and avoid crashes
- Terrain following: Maintaining a constant altitude even when the ground is uneven

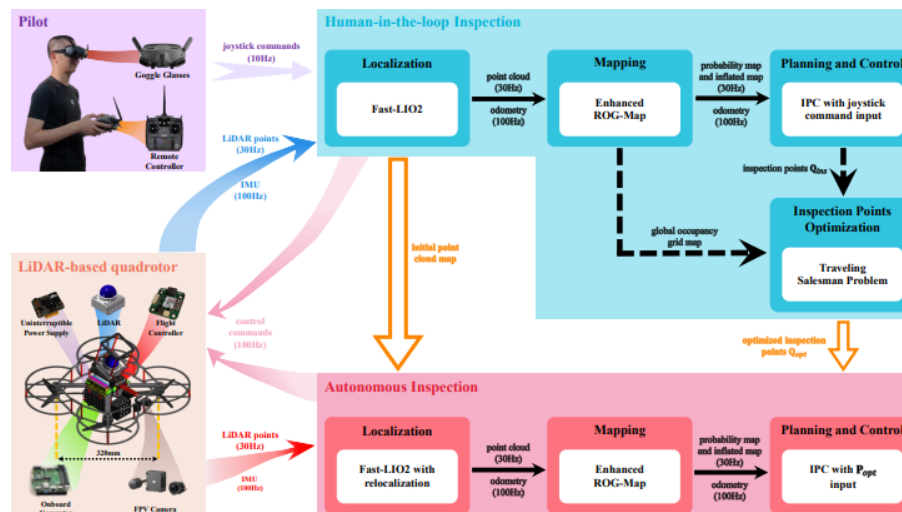


Figure 4: System overview of a LiDAR based quadrotor

The LiDAR Industry and Market Landscape

LiDAR has evolved from a niche technology into a strategic growth. Over the past five years, this field has seen a rise of innovation, and competition.

Leading Companies and Technologies

Velodyne Lidar, Inc.

- Pioneer of spinning 360° mechanical LiDAR
- Historically dominant in early autonomous vehicle (AV) programs (e.g., Google/Waymo)
- Recently merged with Ouster in 2023 to consolidate R&D and reduce costs

Ouster

- Focuses on digital LiDAR chips with simpler architecture
- Acquired Sense Photonics to expand solid-state portfolio
- Competes aggressively on cost per unit

Hesai Technology

- Chinese market leader in automotive and industrial LiDAR
- Became publicly listed on Nasdaq in 2023
- Supplies robotaxis (e.g., Baidu Apollo) and advanced driver-assistance systems

Waymo

- Alphabet's autonomous vehicle division
- Designs proprietary in-house LiDAR optimized for robotaxis
- Licenses technology selectively to partners

Apple

- Integrates LiDAR into consumer devices (iPad Pro, iPhone Pro) for AR and spatial mapping
- Demonstrates how miniaturized sensors can scale to hundreds of millions of units

Spatial Computing and the Role of LiDAR

The integration of digital and physical spaces, where computer systems view, map, and engage with the real world in three dimensions, is known as "spatial computing". It helps place useful business data, like inventory or logistics, onto real spaces, making it easier to understand situations and make better decisions.

LiDAR plays a central role by:

- Providing exact 3D geometry, important for mapping, tracking changes, and analyzing assets inside digital twins
- Facilitating immersive collaboration, predictive operations, and cross-functional innovation for industries like manufacturing and retail (Raskovich et al., 2024).

Conclusion

LiDAR technology serves as a foundation of next-generation perception systems, providing reliable and accurate 3D information across a broad range of applications.

Advancements in solid-state designs and embedded have lowered costs and made LiDAR more useful, especially in robots, drones, and self-driving cars. However, even with these improvements, LiDAR still faces challenges like reduced performance in bad weather and the need for heavy data processing. Combining LiDAR with other sensing technologies like cameras and radar have helped to overcome these limits. As LiDAR technology and sensor fusion methods improve, it will remain a key part of autonomous systems and spatial computing, linking the physical and digital worlds.

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Takla Sassine is a master's student in Electrical Engineering at the University of Balamand, specializing in control systems and automation. She is currently working on obstacle avoidance in drones.

Takla has completed internships at Liban Cables by Nexans and Cimenterie Nationale, where she gained practical experience and developed her technical skills. During her academic journey, she has been an active member of IEEE and currently serves as the Chair of the IEEE Women in Engineering Affinity Group at UOB. In this leadership role, she organizes technical workshops, events, and mentorship programs aimed at supporting and inspiring future female engineers.