Journal of Electronic Research and Application, 2025, Volume 9, Issue 5
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Exploration of the Evolution of LiDAR Technology

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Abstract: Since its inception in the 1960s, light detection and ranging (LiDAR) technology has demonstrated great potential in various fields such as autonomous driving, robot navigation, and environmental monitoring due to its high precision, high resolution, and strong anti-interference capability. This paper reviews the development history, technical principles, application fields, and future development trends of LiDAR technology. It introduces the technical applications of LiDAR technology in autonomous driving, robot navigation, and environmental monitoring, and explores the development direction of SLAM algorithms in multi-sensor fusion and real-time map construction, providing a reference basis for the development and research of LiDAR.

Keywords: LiDAR; Autonomous driving; Robot navigation; Environmental monitoring

Online publication: October 15, 2025

1. Introduction

Light detection and ranging (LiDAR), as an advanced active remote sensing technology, measures the distance, position, velocity, and other information of target objects by emitting laser beams and receiving their reflected signals. It has the advantages of high precision, high resolution, and strong anti-interference ability. With the rapid development of technologies related to autonomous driving, robot navigation, environmental monitoring, and other fields, LiDAR technology has received widespread attention and application [1]. This paper aims to provide a reference for further research and application of LiDAR technology by systematically reviewing its development history, technical principles, application status, and future trends.

Since the first ruby laser was developed by American scientist Maiman in the 1970s, LiDAR technology has experienced rapid development. Foreign countries started research on LiDAR technology earlier and have accumulated rich technical experience. From the initial laser rangefinders to two-dimensional scanning LiDAR, and then to three-dimensional scanning vehicle-mounted LiDAR, foreign LiDAR technology has been continuously iterated and upgraded. Currently, in the global LiDAR industry, companies such as Velodyne (USA), TopoSys (France), IBEO (Germany), and Sick (Germany) occupy leading positions due to their technological advantages [2].

Compared to the research level of other countries, China started its research in the field of LiDAR technology relatively late. However, after rapid development in recent years, and with the support of national key research and development programs, it has achieved international leading results in the fields of single-photon avalanche diodes and superconducting nanowire single-photon detectors. Solid-state LiDARs developed by companies such as Huawei and DJI have achieved mass production. Domestic universities and research institutions have accumulated relatively deep technical expertise in laser technology through years of research, but are relatively lagging behind in the commercialization of laser products. With the rise of the autonomous driving industry, domestic LiDAR manufacturers such as RoboSense, SureStar, and LeiShen Intelligent have emerged, and their products have gradually gained market recognition.

However, compared with leading foreign products, domestic LiDAR still lags behind in accuracy and stability, requiring continuous investment in research and development.

2. Laser radar technology principles

2.1. Basic principles of laser radar

Laser radar emits laser pulses and receives echo signals reflected by target objects, using the time difference between the transmitted and received signals to calculate information such as the distance and velocity of the target objects. This process includes four main stages: laser emission, signal propagation, echo reception, and signal processing. According to different ranging principles, laser radar can be divided into triangulation laser radar and time-of-flight (TOF) laser radar.

Triangulation laser rangefinders use the triangular relationship formed by the reflection point of a laser beam on the surface of a target object and the transceiver to measure distance. These laser rangefinders consist of a laser emitter and a receiver, where the receiver can be regarded as a pinhole camera model. The emitter emits a laser beam, which is reflected when it reaches the surface of an object, and the reflected beam is captured by the receiver.

As shown in **Figure 1**, there is a certain distance between the emitter and the receiver, which is called the baseline length s. By measuring the position change of the reflected beam on the receiver, the distance of the target object can be calculated according to the trigonometric formula, combined with the known baseline length and angle information. However, the measurement accuracy of triangulation LiDAR is greatly affected by the distance of the target object, and the accuracy decreases significantly during long-distance measurement.

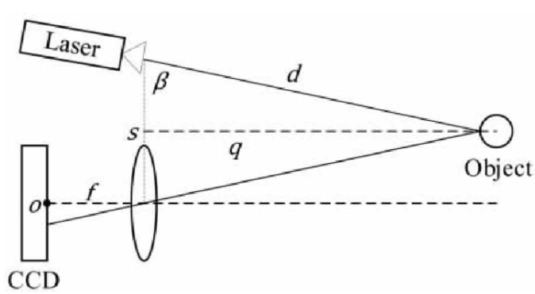

Figure 1. Principle diagram of triangulation laser rangefinder [2]

As shown in **Figure 1**, the linear distance between the emitter and the target object is d, the angle between the baseline and the emitter's optical axis is β, the distance between the target object and the baseline is q, the center of the linear CCD is point o, the focal length of the lens and the CCD chip is f, and the distance between the projection point of the reflected optical axis on the CCD and point o is x. Then:

TOF LiDAR calculates the distance between the LiDAR and the target object by measuring the time it takes for a laser pulse to travel from emission to reception (**Figure 2**) [3]. Its internal timer records the moment of laser emission and the moment of reception, and the measured distance is obtained by calculating the product of the time difference and the speed of light [4]. Although TOF LiDAR has the advantages of small size and strong anti-interference ability, its measurement accuracy is limited by the timing accuracy of the timer, and the power consumption is large.

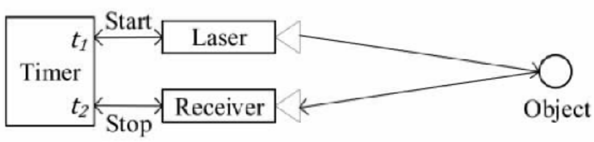

Figure 2. TOF LiDAR principle diagram [2]

The time difference t_2-t_1 calculated based on the laser emission time t_1 and reception time t_2 recorded by the internal high-precision timer, is called time of flight. Given the speed of light c, the observation distance d can be calculated as:

2.2. LiDAR key technologies

As the principle of LiDAR indicates, the precise measurement of LiDAR relies on the processing of information from its transmitted and received signals. Therefore, the accuracy of LiDAR's signal transmission and reception is one of the core key technologies to ensure its signal precision. High-power and high-stability laser transmitters can ensure the energy density and directionality of the laser beam, improving ranging accuracy and anti-interference ability [5]. At the same time, high-sensitivity receivers can accurately capture reflected beams, improving the accuracy and reliability of signal processing.

In practical application scenarios, the echo signals received by LiDAR are susceptible to environmental factors, often mixed with noise or interference signals generated by other devices, requiring signal processing algorithms to complete key processing steps such as filtering, denoising, and feature extraction [6].

To mitigate the negative impact of environmental noise and interference on signal quality, signal processing algorithms have become one of the core key technologies of LiDAR. Commonly used signal processing algorithms include basic algorithms such as threshold detection, peak detection, and correlation detection [7]. In addition, for multi-target detection and tracking requirements, higher-order signal processing algorithms such as cluster analysis and Kalman filtering are also required.

3. LiDAR technology applications

3.1. Autonomous driving field

As a benchmark field for the integration of artificial intelligence and the automotive industry, autonomous driving technology relies heavily on multi-sensor fusion solutions for its technological breakthroughs. Among them, LiDAR, with its centimeter-level ranging accuracy and 3D environment modeling capabilities, has become an indispensable core sensor in future L4/L5 autonomous driving systems. By integrating multi-line LiDAR, autonomous vehicles can build high-precision 3D environment models in real time, enabling functions such as obstacle detection, path planning, and decision control [8].

The perception of the surrounding environment can be achieved using LiDAR. The accuracy of environmental perception is affected by the number of lines, scanning frequency, wavelength, and algorithm processing capabilities of the LiDAR. High-line LiDAR can provide denser point cloud data, improving the detail and accuracy of environmental perception. Currently, L3 and autonomous driving systems are typically equipped with LiDAR. LiDAR-based environmental perception has the advantages of high resolution, high accuracy, and strong anti-interference ability, but it is costly, and its performance degrades in adverse weather conditions (such as heavy rain, heavy snow, and dense fog).

Although LiDAR has significant advantages in accuracy, its cost is high, accounting for nearly half of the entire perception system's cost. Breakthroughs in solid-state LiDAR technology will greatly reduce the cost of LiDAR, facilitating the popularization of LiDAR applications. How to reduce costs while ensuring accuracy, and improve the stability and reliability of LiDAR in harsh weather conditions, are the main challenges currently faced.

Autonomous driving technology is a hot research topic nowadays, and vehicle localization is a core problem that must be solved in autonomous driving technology. A fast and accurate localization system can not only effectively help vehicles achieve autonomous driving functions, but also significantly improve vehicle safety. High-definition maps are the technical guarantee for autonomous vehicles to achieve precise positioning and route navigation, and LiDAR is a crucial sensing device for building high-definition maps [9].

Compared to traditional vehicle navigation systems, modern vehicles with autonomous driving capabilities primarily rely on the matching accuracy of LiDAR and high-precision maps, as well as the performance of SLAM algorithms, for positioning and navigation accuracy. Using LiDAR for positioning and navigation has the advantages of high precision and real-time performance, but it relies on pre-built high-precision maps, and whether the maps can be updated accurately and in a timely manner in large-scale dynamic environments is a challenge.

3.2. Robotics navigation field

Lidar also has important applications in the field of robot navigation and is one of the key technologies for realizing autonomous robot movement and obstacle avoidance [10].

The robot's dynamic obstacle avoidance capability is affected by the scanning speed of the LiDAR, data processing capability, and obstacle avoidance algorithm. Fast scanning and efficient data processing can real-time perceive obstacles and make obstacle avoidance decisions [11]. Using LiDAR for dynamic obstacle avoidance has the advantages of real-time performance and accuracy, but false detections and missed detections may occur in complex environments [12,13]. How to improve the obstacle avoidance accuracy and robustness of LiDAR in complex environments, and how to combine other sensor data to achieve multi-sensor fusion obstacle avoidance, are current research hotspots.

The field of robot navigation also requires the support of SLAM technology, the performance of which is affected by the point cloud quality of LiDAR, algorithm complexity, and computing resources [14]. High-quality point cloud data and efficient algorithms can improve the accuracy and real-time performance of SLAM [15]. SLAM technology using LiDAR can realize the autonomous localization of robots and the map construction of the surrounding environment, but it requires a large amount of calculation and high hardware resources. How to optimize the SLAM algorithm to reduce the amount of calculation, and how to implement efficient SLAM on resource-constrained robot platforms are the main challenges currently facing.

3.3. Environmental monitoring field

In the field of environmental monitoring, LiDAR, with its significant advantages of strong beam directivity and high energy density, can achieve high-precision detection of atmospheric parameters, temperature and humidity, terrain and geomorphology, and other parameters [16,17].

However, in actual atmospheric environment monitoring, its measurement accuracy will be affected by multiple factors such as wavelength, emission power, and real-time atmospheric conditions.

When using LiDAR for atmospheric environment monitoring, its accuracy is affected by the wavelength and emitted power of the LiDAR, as well as atmospheric conditions. Appropriate wavelengths and emitted power can enhance the monitoring range and sensitivity. The application of LiDAR atmospheric environment monitoring technology has the advantages of high precision and high spatiotemporal resolution, but its equipment cost is high and requires professional operation and maintenance. These factors limit its large-scale application. Reducing equipment costs and improving the stability and reliability of LiDAR under different atmospheric conditions are current problems that need to be solved.

The accuracy of terrain and geomorphological monitoring using LiDAR is affected by the scanning method of the LiDAR, point cloud density, and data processing algorithms. The selection of airborne or terrestrial scanning methods, as well as efficient point cloud processing algorithms, can improve the accuracy and efficiency of monitoring. In atmospheric detection, the terrestrial scanning method utilizes the frequency of atmospheric backscattered light to measure temperature and wind speed in the direction of the light beam. Airborne LiDAR uses the differential absorption method to measure surface reflectance at different laser wavelengths to determine the mixing ratio of various gases in the atmosphere [2]. In terrain detection, LiDAR terrain and geomorphological monitoring have the advantages of high precision and rapid imaging, but are greatly affected by terrain complexity and vegetation cover.

How to improve the monitoring accuracy of LiDAR in complex terrain and vegetation-covered areas, and how to achieve automated processing and analysis of monitoring data, are current research directions.

4. Conclusion

As an advanced active remote sensing technology, LiDAR plays an important role in autonomous driving, robot navigation, and environmental monitoring. With the continuous advancement of LiDAR technology and the expansion of application scenarios, LiDAR technology is developing towards higher precision, lower cost, and smaller size. At present, significant achievements have been made in LiDAR technology research both domestically and internationally, but there is still room for improvement in the accuracy and stability of domestic LiDAR.

The future development trends of LiDAR technology will be as follows: First, high precision, which improves ranging accuracy and measurement resolution by optimizing laser emission and reception technology, signal processing, and algorithms; Second, low cost, which reduces the cost of LiDAR through large-scale production and technological innovation, promoting its market application; Third, miniaturization and integration, which achieves miniaturization and integrated design of LiDAR through micro-electro-mechanical systems and other technologies to meet the needs of more application scenarios. With the rapid development of autonomous driving, robot navigation, environmental monitoring, and other fields, the application prospects of LiDAR technology will be broader. In the field of autonomous driving, LiDAR will become one of the key sensors for achieving L4/L5 level autonomous driving; In the field of robot navigation, LiDAR will promote the intelligent upgrade of service robots, industrial robots, and other products; In the field of environmental monitoring, LiDAR will play a greater role in atmospheric environmental monitoring, topographic and geomorphic monitoring, and other aspects.

In conclusion, LiDAR technology is in a phase of rapid development, and its broad application prospects and continuous technological innovation will inject new vitality into the development of related fields. In the future, with the continuous maturity of technology and the expansion of application scenarios, LiDAR technology will play an important role in more fields, promoting the intelligentization and automation of related industries.

Disclosure statement

The authors declare no conflict of interest.

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