

Sensor Fusion Applications in Intelligent Driving

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Abstract:

With the rapid development of intelligent driving technology, the role of sensors becomes increasingly pivotal, as these devices serve as the fundamental elements responsible for perception within the system. Their performance and accuracy are directly correlated with the overall reliability and safety of the intelligent driving system. This article systematically introduces the current application status and technological characteristics of different sensors (including visible light, millimeter wave radar, and lidar) in intelligent driving systems. This article conducts a comprehensive analysis of various sensors' strengths and limitations in complex urban environments, particularly focusing on their performance in high-density traffic scenarios and adverse weather conditions. Based on these findings, the study proposes an optimized multi-sensor fusion solution specifically designed for urban road networks that considers both cost-effectiveness and reliability. Furthermore, it explores emerging technological directions for next-generation urban traffic sensing systems, including vehicle infrastructure cooperative perception and AI-enhanced sensor fusion, discussing their potential applications in smart city development and analyzing the key technical and standardization challenges in their implementation.

Keywords: Intelligent driving; sensor fusion; environment sensing.

1. Introduction

Intelligent driving, as an interdisciplinary field between artificial intelligence and automotive engineering, is gradually reshaping the way people travel. Its core relies on real-time environmental perception by sensors to support decision-making and control [1]. However, a single sensor has inherent limitations,

such as the performance decline of visible light sensors in low light conditions, insufficient resolution of millimeter-wave radars, and the high cost of lidar. These challenges are particularly prominent in urban scenarios, involving complex road structures, dynamic obstacles, and variable weather conditions. Adopting sensor fusion technology is an effective strategy to address these challenges and is also a trend for fu-

ture development. This technology needs to be combined with algorithm optimization to adapt to the challenges of complex environments [2].

This article focuses on the comparison and scenario adaptation of different sensors in intelligent driving. The purpose of research is to propose a sensor fusion strategy tailored for urban scenarios through comparative analysis. The research method employs literature review, combined with case studies: firstly, this paper sorts out the application cases of visible light, millimeter-wave radar, and lidar; secondly, principles and limitations of above are listed; and finally, it offers optimization suggestions based on scenario characteristics (such as urban roads, future trends). The research objectives include identifying the performance of each sensor in typical scenarios, providing a combination of fused sensors to enhance system safety and accuracy to adapt to complex urban roads, and looking forward to the direction of collaborative optimization of algorithms and hardware. This study not only fills the gap in existing reviews but also provides a practical framework for industrial practice.

2. The Application of Different Sensors in Intelligent Driving

2.1 Visible Light Sensor Application

Visible light sensors are widely used for daytime target detection and lane recognition. Their monocular cameras implement vehicle and pedestrian recognition through image processing algorithms in autonomous driving systems, with fast processing speeds suitable for high-speed road scenarios. Binocular cameras are used for stereoscopic vision ranging, with high ranging accuracy and low likelihood of false negatives, allowing for precise distance measurement of objects. However, the application of visible light sensors in the automotive field, especially for lane departure detection, has limitations. These mainly manifest as a significant increase in false detection rates under low-light conditions or strong glare environments. Therefore, data fusion with other sensors is necessary to achieve complementary performance enhancements and improvements.

2.2 Millimeter Wave Radar Sensor Application

Millimeter wave radar is renowned for its strong resistance to interference and is suitable for use in rainy and foggy weather conditions; it also has significant advantages in measuring the speed and distance of targets [3]. Millimeter wave radar is widely used in modern automobiles, providing various safety and driving assistance functions. It can be used in adaptive cruise control systems to mon-

itor the speed and distance of the vehicle ahead, automatically adjusting the vehicle's speed to maintain a safe distance and prevent rear-end collisions; it is also used in lane change assistance systems to continuously monitor traffic on both sides and behind the vehicle, enhancing the safety of lane changes; and it is used in forward collision warning and braking assistance systems to detect obstacles or pedestrians ahead, providing early warnings in case of collision risks, and automatically braking when necessary [4].

2.3 LiDAR Sensor Application

LiDAR technology has significant application value in tasks such as positioning, obstacle detection, and environmental reconstruction. It excels in the field of ranging and, due to its immunity to environmental factors such as lighting, can achieve stable operational performance in nighttime or other low-light conditions. Furthermore, LiDAR can precisely measure the distance and speed of target objects by emitting laser pulses and receiving the reflected signals, thereby providing high-precision spatial perception capabilities for autonomous vehicles, drones, and robots. The high resolution and three-dimensional imaging capabilities of this technology also give it a broad application prospect in fields such as archaeology, topographic mapping, and urban planning [4].

3. Sensor Analysis

3.1 Visible Light Sensors

3.1.1 Principle

Monocular cameras are based on 2D image processing, such as feature extraction using the YOLO algorithm, which is computationally efficient but lacks depth information. Binocular cameras calculate distance through disparity, with the basic formula being below formula (1):

$$d = f \cdot \frac{b}{x} \quad (1)$$

In the above formula (1), d is the vertical distance from the target object to the camera baseline, f is the focal length, b is the baseline distance, and x is the disparity. Visible light sensors generally use machine vision algorithms (such as image recognition, deep learning) to efficiently process real-time images, update accurate and real-time information, thereby reducing accidents in autonomous driving of vehicles [5].

3.1.2 Limitations

Under certain lighting conditions and in bad weather, the performance of visible light sensors may be affected,

requiring the integration of other sensors (such as LiDAR, radar) to enhance the accuracy of environmental perception [5]. In comparison, monocular systems are lightweight but have low accuracy, making them suitable for low-cost systems; binocular systems are precise but have poor real-time performance, making them more suitable for high-precision scenarios. However, with technological advancements, monocular systems have seen improvements in accuracy through algorithm optimization and deep learning techniques, while binocular systems are also being improved to enhance real-time processing capabilities, giving each their own advantages in specific applications.

3.2 Millimeter Wave Radar Sensors

3.2.1 Principle

Millimeter wave radar can emit electromagnetic waves, and its measurement principle is based on the spatial propagation characteristics of electromagnetic waves. Based on the Doppler effect, it transmits 77GHz electromagnetic waves, and calculates the distance through the echo delay. The basic formula is shown below:

$$R = \frac{c \cdot \Delta t}{2} \quad (2)$$

In the above formula (2), R is the straight-line distance between the radar and the obstacle, c is the speed of light, and Δt is the time difference between the emission and reception of the electromagnetic wave. When the transmitting device emits a signal, the system starts timing. The electromagnetic wave propagates at the speed of light in the air, encounters obstacles or reflective surfaces, and reflects. The receiver captures the reflected wave and stops timing. By measuring the time difference between transmission and reception, and combining the propagation speed, the distance between the transmitting device and the obstacle can be calculated [4].

3.2.2 Limitations

Millimeter wave radar detects targets by using electromagnetic wave beams and the scattered waves from the target. Due to its operating principle, target detection is susceptible to external interference. In particular, as the detection range increases, ground features and landmarks may generate interfering clutter signals, making target detection more difficult [6]. Moreover, due to the limited resolution of millimeter wave radar sensors, they are not suitable for applications requiring bi-directional identification. Therefore, researchers in the field of autonomous driving typically adopt a strategy of fusing millimeter wave radar data with inputs from other sensors to overcome these limitations [7].

3.3 LiDAR Sensors

3.3.1 Principle

When the laser emission device emits a laser beam, it starts timing. When the laser hits an obstacle and reflects back, the receiver stops timing upon receiving the reflected signal. The distance to the obstacle is then calculated based on the time taken for the laser to be emitted and returned. LiDAR uses high-frequency laser beams to scan, thereby obtaining three-dimensional point cloud data. These data provide precise spatial information, allowing for detailed measurements of the shape, position, and distance of objects. Consequently, they offer high-precision three-dimensional models for various applications [3].

3.3.2 Limitations

LiDAR detection is significantly affected by weather conditions, with severe weather such as rain, snow, and fog causing a substantial decrease in its detection performance. This is because its operating principle relies on the propagation and reflection of laser beams, and adverse weather conditions interfere with the transmission path and reflection effects. For example, in rainy or snowy weather, laser beams are absorbed and scattered by raindrops or snowflakes; in foggy conditions, they are scattered by fog droplets, thereby weakening the detection effect. Additionally, the high cost of LiDAR also limits its widespread application [3].

4. Suggestions for Sensor Applications in Intelligent Driving

4.1 Characteristics of Urban Road Scenarios

The complexity of urban road environments is mainly reflected in the following aspects: First, the high density of traffic flow, with dense vehicle traffic often leading to traffic congestion and slow driving; second, frequent pedestrian interactions, as people continuously interact with vehicles while crossing the street, getting on and off buses, and shopping, increasing the uncertainty of the road; third, variable weather conditions, with adverse weather such as rain, snow, strong winds, and smog affecting road conditions and driving safety.

4.2 Advantages of Different Sensors in Urban Road Applications

Visible light sensors excel in detail recognition, accurately identifying and analyzing various colors and effectively extracting texture information from the surfaces of objects. They precisely recognize road environments, traffic

signs, pedestrians, and other vehicles. Millimeter-wave radar possesses strong penetration capabilities and excellent resistance to interference, making it outstanding in detecting high-speed moving targets. Additionally, this sensor technology maintains stable performance in harsh weather conditions, ensuring the continuity and accuracy of the monitoring system. LiDAR offers excellent accuracy in 3D modeling at night and precisely detects the position, size, and shape of surrounding objects in complex roads, providing high-resolution spatial information.

4.3 Optimal Sensor Combination for Urban Roads

In complex urban road environments, the failure rate of a single sensor is often high. To address this issue, a multisensor fusion scheme can be adopted, prioritizing the use of visible light sensors and millimeter-wave radars, with low reliance on lidar. This choice is based on the following dual considerations: First, the extensive use of lidar is not only costly in terms of hardware, significantly constraining large-scale deployment; second, the scanning frequencies of lidar and visible light sensors are often difficult to synchronize, leading to a time difference in the collected data, resulting in mismatched information layers in the fused data. This makes it difficult to precisely register the two types of data [8]. Drivers generally do not choose autonomous driving at night, and lidar is mainly used for night environment detection, so the weight of lidar usage can be reduced. In contrast, the fusion scheme of visible light and millimeter-wave radar has a significant cost-effectiveness advantage; visible light sensors can effectively capture the rich details of daytime, while millimeter-wave radar provides robust compensation under adverse weather conditions such as rainy days and foggy days.

For the typical urban complex road conditions characterized by high traffic density, frequent vehicle-pedestrian interactions, and variable weather, this paper proposes and demonstrates that “visible light sensor + millimeter-wave radar + solid-state lidar” is the optimal fusion architecture. The specific deployment is as follows: the visible light sensor preferably selects a binocular camera placed inside the windshield, responsible for high-precision traffic sign recognition and pedestrian texture analysis; the millimeter-wave radar is installed on the bumper to ensure real-time vehicle distance monitoring in all weather conditions, especially in rainy and foggy weather; the solid-state lidar is fixed on the roof, providing accurate three-dimensional ranging information in low-light and nighttime environments. The scheme aims to achieve complementary advantages of sensors: on sunny days, it

mainly relies on the data from visible light sensors; on rainy and foggy days, it switches to being primarily guided by millimeter-wave radar data; at night or in low-light scenarios, perception is based on the three-dimensional point cloud data from the lidar. This scheme theoretically performs excellently on key performance indicators, including pedestrian detection accuracy, vehicle ranging precision, and system response latency, especially in rainy and foggy weather, where the false detection rate is effectively controlled within an extremely low range.

4.4 Future Scenarios

From the perspective of roadside integrated perception application fields, market demand, and current technological status, multisensor fusion is an inevitable trend. It integrates data from different sensors to obtain more comprehensive and accurate environmental information, which can enhance the performance of the perception system, compensate for the shortcomings of individual sensors, and improve the vehicle’s perception and decision-making capabilities in complex environments, as well as the safety of autonomous driving [9]. With algorithm optimization (such as deep learning multisensor fusion algorithms), sensors will develop towards lighter weight and lower power consumption. In a vehicle-road cooperative environment, sensor data sharing with infrastructure enhances overall robustness [10].

To improve object detection performance in various scenarios, including adverse weather conditions, and to achieve safe and reliable scene perception, further technological improvements are needed. On one hand, existing sensor fusion algorithms can be improved through deep learning or deep reinforcement learning [11]. On the other hand, investing in the technology related to sensor hardware can significantly enhance the environmental resolution, thereby bolstering the security features of large-scale models. This increased investment can help these models to better withstand various forms of external malicious attacks, including unauthorized remote control and data tampering attempts. By upgrading sensor hardware, the systems are equipped with more sophisticated detection mechanisms and protective measures, making it considerably more difficult for potential attackers to compromise the integrity and security of the data and system [12]. In addition, companies and researchers need to assess failure risks and provide alternative solutions for drivers in the worst-case scenarios [13].

5. Conclusion

This article systematically reviews the applications, working principles, and adaptability of visible light sensors,

millimeter-wave radar, and lidar in the field of intelligent driving, as well as their unique advantages in specific scenarios through comparative analysis. Each sensor has its distinctive strengths under certain conditions: visible light sensors excel at target recognition during daytime, millimeter-wave radar shows stable and reliable performance in harsh weather conditions, and lidar provides high-precision three-dimensional reconstruction. However, a single sensor solution has certain limitations, necessitating sensor fusion to complement each other's shortcomings.

In response to the characteristics of urban scenarios, such as high dynamics and variable environments, this article proposes corresponding optimization suggestions, advocating for the fusion of visible light sensors with millimeter-wave radar and low-dependency lidar in urban road environments to achieve a balance between performance and cost. This fusion scheme can better cope with the complexity of urban roads and enhance the overall performance of intelligent driving systems.

Look into the future, sensor technology will develop towards multimodal fusion. Changes in scenarios will drive continuous technological evolution. On the one hand, algorithm optimization, such as fusion models based on deep learning, will significantly improve the efficiency of data processing; on the other hand, the miniaturization and cost reduction of sensor hardware will facilitate its large-scale application. In addition, the introduction of vehicle-road cooperation technology and 5G communication will expand the sources of sensor data, achieving global perception. These trends will greatly promote the realization of higher safety and reliability for intelligent driving technology in complex urban environments. The impact of this research is to provide a design framework for the intelligent driving industry and suggest that future work should focus on the research of real-time fusion algorithms and the development of standardized test scenarios. Through these efforts, intelligent driving systems will be better equipped to handle various complex scenarios in practical applications, thereby providing drivers with a safer and more reliable driving experience.

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