GEORGE BROWN PRESS
JOURNALS, BOOKS & PROCEEDINGS

International Journal of Engineering Advances

Review

Intelligent Sensor and System Integration Optimization of Auto Drive System

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Abstract: With the rapid advancement of autonomous driving technology, the deployment of advanced sensor systems has become a cornerstone for achieving high-precision environmental perception, supporting real-time decision-making, and executing vehicle control operations. These sensors-including LiDAR, radar, cameras, ultrasonic modules, and inertial measurement units-provide critical data streams that enable vehicles to perceive dynamic and complex driving environments accurately. However, despite these technological advancements, significant challenges remain in sensor system integration and data fusion. Common issues include asynchronous operation among sensor modules, suboptimal physical layout affecting system performance, excessive communication and computational loads, and difficulties in synchronizing multimodal data streams, all of which limit the overall efficiency, responsiveness, and reliability of the autonomous driving system. This paper systematically analyzes the application of advanced sensor technologies within autonomous driving systems, examining the functional characteristics, strengths, and limitations of various sensor modules for environmental perception, positioning, and decision-making assistance. Special attention is given to the core difficulties encountered in multi-sensor integration, including data synchronization, signal redundancy, energy consumption, and system scalability. To address these challenges, the study proposes key solutions such as optimized integration mechanisms, efficient sensor layout design, energy-aware communication strategies, and advanced data fusion algorithms. These measures aim to enhance system stability, increase processing speed, improve compatibility with diverse environmental information, and enable real-time, reliable vehicle operation under complex driving scenarios. Through these integrated strategies, the paper demonstrates how the combination of optimized sensor deployment, efficient data fusion, and systematic integration design can significantly elevate the performance level of autonomous driving systems. The findings provide a technical foundation for the large-scale deployment and practical application of intelligent sensor equipment, contributing to safer, more efficient, and highly reliable autonomous vehicle operations in real-world environments.

Keywords: intelligent sensors; system integration; autonomous driving; optimization strategy

Received: 23 October 2025
Revised: 06 November 2025
Accepted: 02 December 2025
Published: 07 December 2025

1. Introduction

Autonomous driving represents the future mainstream of intelligent transportation and is rapidly transitioning from an experimental research phase to market-oriented, large-scale deployment. The effectiveness, safety, and adaptability of autonomous vehicles heavily depend on the perception, decision-making, and control layers, with intelligent sensors forming a critical component of the perception layer. These sensors-including LiDAR, radar, cameras, ultrasonic modules, and inertial measurement units-directly influence the vehicle's ability to accurately perceive the surrounding environment, assess dynamic conditions, and execute timely and reliable control actions.

As autonomous driving technology advances, the complexity of sensor systems has increased significantly, making the efficient collaborative operation of integrated sensors a core challenge. The design, layout, and optimization of multi-sensor systems are constrained by several technical bottlenecks, including difficulties in real-time data synchronization, suboptimal hardware placement, high communication bandwidth requirements, and excessive energy consumption during information exchange. These factors collectively limit the overall system efficiency, response speed, and robustness of autonomous vehicles under complex and dynamic driving conditions.

Given these challenges, this article focuses on the current application status of intelligent sensor technologies within autonomous driving systems. It systematically analyzes the key issues present in multi-sensor integration and fusion, including signal misalignment, redundancy, latency, and interference. Based on this analysis, the study proposes targeted optimization strategies-such as integration mechanism refinement, layout design improvement, energy-efficient communication management, and advanced data fusion algorithms-to enhance both the operational stability and reliability of autonomous driving systems. The proposed approaches not only provide practical engineering solutions but also contribute to the broader objective of achieving safe, efficient, and highly adaptable unmanned driving in real-world environments.

2. Overview of Auto Drive System

In recent years, autonomous driving technology has rapidly developed due to its significant importance for future intelligent transportation. According to the Society of Automotive Engineers (SAE) standards, autonomous driving is divided into six levels, L0 to L5, covering various stages from manual driving to full automation. With the maturity of artificial intelligence, Internet of Vehicles, big data and high-precision positioning technology, autonomous vehicle have achieved small-scale road testing and are being promoted to large-scale applications [1].

The auto drive system mainly includes three modules: perception, decision-making and execution. By collecting environmental data through various intelligent sensors, the system provides basic support for path planning and driving decisions. Based on the perceived information, the system analyzes the traffic environment and regulations, formulates the optimal driving plan, and converts the decision results into specific control instructions to ensure driving safety and continuity. Sensors play a crucial role in the system, as their accuracy, reliability, and environmental adaptability directly determine overall performance [2]. With the increasing complexity of application scenarios and the growing demand for sensor performance, how to enhance the accuracy and stability of perception systems has become an important direction in current technological research.

3. Application of Intelligent Sensor in Auto Drive System

3.1. Construction of Environmental Perception System

Environmental perception is one of the fundamental components that directly affects the acquisition of external environmental information by autonomous vehicles, as well as the effectiveness of path planning and safe driving processes. To achieve comprehensive and accurate acquisition of external information, various perception devices are generally used in autonomous driving. Lidar positioning determines the three-dimensional coordinates of an object; Millimeter wave radar is not limited by severe weather conditions such as rain, snow, and haze, and can still stably detect the relative speed and distance of targets; The camera mainly obtains semantic information such as road signs, lane markings, traffic lights, etc., to enhance situational analysis ability. To ensure the reliability of environmental perception, a fusion processing method of multiple sensors is usually adopted. The commonly used method is to use a weighted fusion model to fuse the results observed by each sensor based on their credibility. The fusion formula is as follows:

$$\hat{x} = \sum_{i=1}^{n} w_i x_i \tag{1}$$

Among them, $\hat{x}$ For the fused estimate,x_iFor the observation data of the i-th sensor, w_i To correspond to the weight and satisfy $\sum_{i=1}^{n} w_i = 1$. Through integration, the advantages of various devices can be fully utilized under different environmental conditions, improving overall perception accuracy and stability. The environmental perception system also needs to meet real-time requirements to ensure rapid response in complex and dynamic traffic environments, providing reliable support for subsequent decision-making and control [3].

3.2. Support for Positioning and Navigation Systems

Accurate location and navigation information are important factors in achieving safe driving and trajectory planning for autonomous vehicles. The system typically obtains accurate position information through technologies such as Global Navigation Satellite System (GNSS), Inertial Navigation Unit (IMU), and Visual Odometry [4]. Among them, GNSS has a certain degree of certainty and can provide real-time latitude and longitude positions for vehicles. However, due to geographical factors such as signal obstruction in tunnels, urban canyons, etc., the accuracy may be reduced; IMU can detect real-time acceleration, rotation and other data of the vehicle body, but due to the cumulative effect, the error gradually increases; Visual odometry uses image feature point pairing to estimate relative movement distance, which can supplement the areas where other sensors are not proficient. The most accurate and reliable method for achieving global positioning is to fuse sensor information with Extended Kalman Filter (EKF). The prediction update process can be described by the following formula:

$$\hat{x}_i = \hat{x}_{k-1} + k_k(z_k - H\hat{x}_{k-1}) \quad (2)$$

Among them, $\hat{x}_k$ For the state estimation at time k, z_k For observation values,HTo observe the matrix, K_K For Kalman gain. By dynamically adjusting the weights of the observed values of each sensor, EKF can achieve high reliability positioning output under different environmental conditions. The comprehensive positioning results not only support the path planning module to formulate the optimal driving route, but also provide continuous and stable position information input for vehicle execution control [5].

3.3. Information Assurance of Control System

The execution module of autonomous driving is the control system of the car, which precisely defines the commands fed back by the sensing and decision-making modules as a turning, acceleration, or braking operation. In order to achieve high-precision tracking of the path and ensure stable control during driving, it needs to continuously receive environmental data information and positioning feedback, which is provided by the induction and positioning module. The motion response of the car is usually achieved through a path tracking controller to ensure that the car travels smoothly and safely along the given path. Error calculation is a crucial step, and trajectory tracking error can be expressed as:

$$\mathrm{e(t)} = \mathcal{Y}_{\mathrm{ref}}(\mathrm{t}) - \mathrm{Y(t)} \quad (3)$$

Among them, e(t) is the trajectory tracking error at time t, $\mathcal{Y}_{ref}(t)$ To reference the trajectory position, $\mathcal{Y}(\mathrm{t})$ After being monitored by the control equipment, the live vehicle adjusts its turning angle and acceleration/deceleration according to different deviation values, ensuring that the vehicle continuously approaches the planned route during the driving process. In addition, in order to adapt to the anti-interference of the control system and achieve the perfection of the self-driving control system, it is necessary to continuously detect abnormal states of sensors and quickly switch to backup solutions, thereby ensuring safety and smoothness in complex road environments. High quality input information and precise deviation control methods are prerequisites for the normal and stable operation of the control management system.

4. The Problems of Intelligent Sensors in System Integration

4.1. Lack of Coordination in Multi-Source Data Fusion

Multi source data fusion is the core technology of auto drive system perception, but there are many collaboration problems in practical applications. Lidar, millimeter wave radar, cameras, and ultrasonic detectors have differences in acquisition speed, time labeling, output format, and accuracy, which can easily lead to inconsistent data before fusion. The time alignment error is particularly prominent, and if the sampling lag is not corrected in a timely manner, it will make it difficult for the fusion algorithm to accurately capture road changes, affecting the effectiveness of path planning and decision-making.

The spatial positioning error is equally severe. The installation deviation of the equipment and the vibration and temperature changes during operation cause the sensor position system to gradually drift, and the fusion accuracy decreases over time. The difference in the observation delay of different sensor sources for the same target further aggravates the perception bias in the dynamic scene. Information conflicts increase the instability of fusion algorithms, indirectly weakening the accuracy of environmental perception and the robustness of the system.

4.2. System Layout Design and Functional Collaboration Are Limited

In autonomous vehicle, sensor layout directly affects the efficiency of the collaborative work between perceived quality and vehicle. Due to limitations in vehicle structure and exterior design, sensor installation space is limited, making it difficult to balance optimal visibility and equipment protection. This can lead to blind spots or insufficient coverage, resulting in incomplete and inaccurate environmental modeling.

During the assembly process, electronic interference, optical obstruction, and heat accumulation are commonly present, and interference between millimeter wave radar and cameras is intensified, resulting in observation data easily deviating from normal values. High temperature equipment such as LiDAR operates in narrow spaces, causing performance fluctuations due to heat accumulation and shortening its service life. As the usage time increases, vehicle vibration, temperature changes, and mechanical wear cause small displacement of components, leading to a decrease in coordinate system accuracy, data fusion accuracy, and system stability. The problem of limited layout and collaboration has become one of the key factors that restrict the performance improvement of the auto drive system.

4.3. Increased Pressure on Communication Networks and Energy Management

In the environment of the auto drive system, many sensors will continuously output a large amount of hot information, which challenges the network communication inside the vehicle. If the onboard system simultaneously activates the laser radar, high-definition camera, and microwave radar, the flow of data during transmission will show an explosive upward trend. Therefore, the original communication channel is prone to bandwidth bottlenecks and transmission delays, indirectly affecting the timeliness and effectiveness of sensing information. When there is a large workload, the communication path often experiences data loss or transportation congestion, which will greatly affect the system's fast response performance to complex road scenarios. For the central processing unit, it needs to occupy more resources to process hot big data. Due to the increased workload of core components such as CPU and GPU caused by high-frequency large data streams, the power consumption of the entire system is constantly increasing. The increase in this type of electricity will indirectly increase the difficulty of heat dissipation and have a profound impact on the driving distance of autonomous vehicles, leading to long-term constraints on high-density autonomous driving operations (As shown in Figure 1).

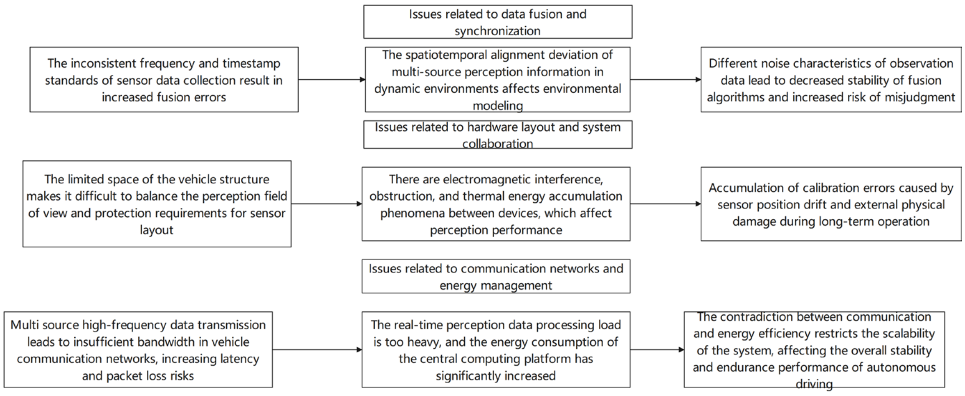

Figure 1. Problems of Intelligent Sensors in System Integration.

The contradiction between communication efficiency and energy consumption management is becoming increasingly prominent, especially in multi-sensor systems. There is a natural conflict between the communication requirements of high bandwidth and high reliability and the design goals of low energy consumption and lightweight, which poses continuous challenges to system integration design. This problem has become an important factor restricting the performance improvement and large-scale deployment of the auto drive system.

5. Optimization Strategy of Intelligent Sensors in System Integration

5.1. Improve Data Fusion Consistency and Real-Time Performance

Improving the comprehensive performance of data requires starting from aspects such as time continuity, time synchronization consistency, fusion structure, and computational efficiency. Based on high-precision PTP (Precision Time Protocol) synchronization, microsecond level clock alignment is achieved to fuse various sensor data in a unified time frame. Adopting a hierarchical fusion architecture, targeted fusion algorithms are used at different levels to improve data processing speed and fusion effectiveness.

In terms of resource scheduling, some basic data processing can be completed in the edge computing unit, reducing the central computing pressure and response delay. For example, in some L3 level autonomous driving platforms, the data from millimeter wave radar and cameras are preprocessed locally to generate an obstacle list, and only key feature information is uploaded, effectively reducing data volume and improving fusion real-time performance. Through precise synchronization, hierarchical processing and edge computing, the perception accuracy and system response speed can be guaranteed at the same time, and the overall automatic driving performance can be significantly improved.

5.2. Optimize Hardware Layout and System Collaborative Design

Reasonable and effective hardware configuration planning can significantly improve the overall efficiency and stability of the entire sensing system for the integration of sensor groups. To achieve optimal spatial layout optimization, the coverage requirements of full scene perception are integrated with the structural characteristics of the vehicle itself to reasonably configure the spatial positions of various sensor modules, so that they have the optimal field of view and the smallest possible blind spots. From the perspective of the effective detection field of view of sensors and the risk of obstruction, based on simulation optimization methods, the effective perception area can be increased by about 15% to 20%, and the proportion of blind spots in environmental models can be reduced by nearly 18%, further improving the perception integrity for complex scenes. On the other hand, in order to enhance the pertinence of layout optimization, doing a good job in electronic compatibility matching is also one of the key measures. The sensor module and high-frequency communication lines inside the vehicle are kept at a certain distance and equipped with isolation and shielding lines to avoid the increase of observation deviation caused by electromagnetic effects. The use of separate placement and anti-interference material arrangement methods for laser radar and millimeter wave radar that are susceptible to interference can reduce the proportion of signal interference by more than 30% and improve the accuracy of radar target recognition by at least 25%.

Optimize thermal management. Place high-temperature equipment in the optimal position for airflow, and optimize the placement sequence of equipment based on the simulation of heat source location to improve the overall system's heat dissipation. For example, an autonomous vehicle reduced its surface temperature by 12% and extended its overall operating time by 17% by rearranging its LiDAR and computing units, greatly improving the device's lifespan and stability. Comprehensive consideration of electromagnetic compatibility and reasonable requirements for thermal management, layout, and collaborative design can promote long-term stable operation of the system, ensuring efficient sensing and safe handling of autonomous vehicles in complex environments (As shown in Table 1).

Table 1. Optimization of Hardware Layout and System Collaborative Design.

Optimize the project	Improvement range of indicators
Effective perception area enhancement	15%~20%
Reducing blind spots in environmental modeling	18%
Reduced signal interference rate	30%
Improvement of radar detection accuracy	25%
Surface temperature decrease	12%
Continuous working hours increase	17%

5.3. Strengthen Communication Efficiency and Energy Consumption Management Mechanism

In order to enhance the communication efficiency and energy efficiency of intelligent perception systems, in addition to optimizing network hardware performance and traffic scheduling, it is also possible to use Ethernet with higher bandwidth combined with the Time Sensitive Network (TSN) protocol of synchronous Ethernet to reduce message transmission delay and enhance instant information communication capabilities; The introduction of priority traffic scheduling technology in automotive networks prioritizes the transmission of critical information, thereby improving bandwidth utilization efficiency and enhancing the collaborative processing capabilities of multiple sensors. The local pre-processing and compression technology on the device side can greatly compress the initial data volume, which can reduce the burden of data stream transmission rate by about 40%, thus reducing the pressure on the communication link. For example, a commercial auto drive system reduces the data stream demand of the camera by 50% by extracting some features, thus improving the reliability and timeliness of the entire system.

On the premise of satisfying the perception performance, the total power consumption can be reduced by about 15% by controlling the working power consumption configuration of sensors and computing units, which is the contribution of coordinated communication and power optimization methods to the operation and endurance of the future auto drive system.

6. Conclusion

As the core component of the sensing layer of the auto drive system, intelligent sensors are the foundation of the whole process of environment cognition, path planning, control execution, etc. of autopilot. By analyzing the application of sensors in environmental perception, positioning, and control assistance processes, it is found that the difficulty of establishing complex multi-purpose integration and architecture is increasing. At present, there are also problems such as data consistency, rationality of equipment deployment, communication, energy consumption, etc., which are difficult to get satisfactory control and cannot achieve stable operation and large-scale application of the auto drive system. Therefore, this paper proposes a unified time synchronization, optimized layout design, communication frequency and dynamic energy efficiency control mode, and verifies that this mode can improve the comprehensive performance of the perception system, provide a more efficient utilization and intelligent control mode for the comprehensive optimization of auto drive system under the development of intelligent system structure and new sensor technology in the future, and is conducive to promoting the realization of high automation level of auto drive system.

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