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Survey of Autonomous Driving via Multisensor Cooperation

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Abstract

Against the background of rapid progress in science and technology and continuous optimization of intelligent transportation systems, a survey of autonomous driving based on multisensor cooperation has focused on multisensor cooperation technology in the field of autonomous driving. First, the research background, purpose and significance of this technology are introduced, and the value of this technology in theory and practical application is clarified. Second, the concept of multisensor collaboration is expounded, including the characteristics of different sensors, application scenarios, key technologies, architecture, advantages and challenges. Then, the data fusion technology is discussed in detail, including an overview, common methods, applications and limitations in autonomous driving. It also illustrates the application of multisensor collaboration in the perception layer, decision layer and execution layer of an autonomous driving system and shows the effect with a case study. Finally, its importance and potential development direction are summarized, which provides a comprehensive technical reference for related researchers and engineers.

Keywords

multisensor collaboration, data fusion technology, automatic driving, sensor fusion

1. Introduction

1.1 Research Background

With the rapid progress of science and technology and the continuous optimization of intelligent transportation systems, automatic driving technology has attracted increasing attention in the field of modern transportation and has become a key research direction (Chen et al., 2018). The key goal of this technology is to make vehicles intelligent and automatically drive, which can make traffic safer and smoother and reduce energy consumption and environmental pollution. To achieve this goal, multisensor cooperative systems are critical. Multisensor cooperation integrates the data collected by different types of sensors to obtain a more comprehensive understanding of the vehicle's surroundings and provide accurate and reliable information support for system decision-making.

However, each type of sensor has advantages and disadvantages. For example, lidar can detect vehicles with high accuracy and long distances, but it is vulnerable to bad weather. Cameras can capture a large amount of image information, but the effect is poor when the light is bad; millimeter-wave radar has strong penetrating ability, and its ability to recognize small objects is not good. To solve the problem of using only one sensor, multisensor cooperation technology has been developed. By fusing the data of different sensors to complement each other, the multisensor system can perceive the surrounding environment more comprehensively and accurately, which makes the autonomous driving system more reliable and stable. However, there are also many problems in multisensor cooperation, such as complex data fusion algorithms, difficult time and space synchronization between sensors, and the strong computing power required to process large amounts of data.

In this case, research on autonomous driving technology based on multisensor cooperation is highly valuable for both theoretical and practical applications. Combining and analysing the existing technical solutions can clarify the main directions and technical difficulties encountered in the current research and provide a reference for subsequent research. Moreover, studying the shortcomings of multisensor collaboration can reveal new research directions and innovation points to promote the continuous progress of autonomous driving technology.

1.2 Research Purpose and Significance

The main objective of this study was to comprehensively carry out automated driving technology on the basis of multisensor collaboration, carefully combine and analyse the literature, and the research results reveal three to five solutions, as well as the current mainstream technology solutions, and then specify the characteristics of these solutions. Their core technical points and specific implementation methods in key links, such as sensor fusion, data processing, and decision control, are presented. Finally, this study provides a comprehensive technical reference system for researchers and engineers in the field of autonomous driving, helps them more clearly grasp the current status and trend of technology development, and promotes the innovative development and practical application (Li, 2024) of autonomous driving technology.

Automated driving technology based on multisensor collaboration is a key part of intelligent transportation systems and can improve road safety levels, optimize traffic operation efficiency, and reduce environmental pollution. This study systematically summarizes multisensor collaboration technology, summarizes the advantages and disadvantages of existing technology, provides a scientific reference for the future direction of technology development, promotes the cross-integration of multidisciplinary fields, and drives the common progress of sensor technology, data processing algorithms, artificial intelligence and other fields. Finally, this study provides theoretical support and technical reserves for the realization of fully autonomous driving and the wide application of intelligent transportation systems.

2. Overview of Multisensor Collaboration

2.1 Concept of Multisensor Collaboration

Multisensor collaboration is a process in which multiple sensors work together to collect information about the environment and then cooperate to process the information to improve the performance of the system (Li & Qian, 2024).

There are several key technologies in multisensor cooperation. The purpose of data fusion is to collect and integrate the information collected by the four sensor types, as shown in Table 1, and obtain more comprehensive and accurate environmental perception results after comprehensive analysis. Time synchronization should ensure that the time point of each sensor information collection is the same so that there will be no errors in the fusion process; sensor calibration should clarify the position relationship between different sensors and unify the data into the same reference coordinate system. Exception handling adjusts and addresses sensor failure or data anomalies in time to ensure the stable and reliable operation of the system.

Future research may focus on optimizing the data fusion algorithm to make information processing more efficient, improving the time synchronization method to make time matching more accurate, and improving the exception handling technology to increase the system's anti-interference ability. The goal is to further improve the performance and reliability of multisensor cooperation.

Table 1: Concept of multisensor collaboration

Sensor types	Features	Application scenarios
lidar	High-precision range measurement, providing 3D point cloud data	Object detection, environment perception

Cameras	Get rich visual information to recognize objects and scenes	Lane line detection and traffic sign recognition
Millimeter-wave radar	Real-time monitor target speed, distance, strong anti-jamming capability	Vehicle speed monitoring, front target warning
Ultrasonic sensors	Close and accurate measurement, low cost	Parking assistance, obstacle detection

2.2 Key Technologies of Multisensor Collaboration

Multisensor collaboration involves a number of key technologies (Tu et al., 2024). These technologies are composed of a variety of complex algorithms and strategies, and their core objective is to integrate the data of different sensors effectively to comprehensively perceive and accurately identify the target environment. Data synchronization technology is the basis of multisensor collaboration because different sensors usually have different sampling frequencies and data output rates. To ensure that the data have to align with the timestamp, the commonly used method is based on the timestamp of the interpolation method and the design of an adaptive synchronization algorithm based on sensor features. These methods can ensure that each sensor data point is accurately aligned.

The data fusion algorithm of multisensor collaboration is the key, common fusion method with Kalman filter and particle filter and Bayesian networks. The Kalman filter has high computational efficiency and is suitable for linear systems, so it is commonly used for preliminary fusion. The particle filter can address nonlinear and nonGaussian problems, and the fusion accuracy is increased by approximating the posterior probability distribution through the particle set. Deep learning techniques have a new opportunity for multisensor fusion; building multilevel neural networks can automatically extract and integrate multisource heterogeneous data information, significantly improving system awareness and robustness.

The strategy of sensor selection and allocation is also important. Allocating resources reasonably according to the performance characteristics of sensors and specific task requirements can ensure system performance and reduce computational complexity and energy consumption. A multisensor collaboration system needs to have strong fault detection ability and fault tolerance, and real-time monitoring of the working status of each sensor can find and isolate the fault sensors in a timely manner and ensure a continuous and stable operation system. These technologies cooperate with each other to lay a solid foundation for multisensor cooperative systems and provide reliable environmental perception and decision support for complex applications such as autonomous driving and robot navigation.

2.3 Architecture of Multisensor Collaboration

In an automatic driving system, a multisensor collaborative structure is the core framework (Shen et al., 2024) used to realize efficient perception and decision making. Its design idea is to make different sensors work together to compensate for the shortcomings of single sensors and enhance the overall perception ability and stability of the system. This structure generally has four main parts, namely, a data acquisition layer, an information fusion layer, a decision control layer and an application layer.

Table 2: Architecture of multisensor collaboration

Types of architectures	Features	Strengths	Disadvantages
Centralized structure	Centralized processing of sensor data	The precision of data fusion is high	High bandwidth requirement for data transmission and large processing delay
Distributed architecture	Sensors interact after processing data individually	The system has high flexibility and fast processing speed	The accuracy of data fusion is relatively low
Hybrid structure	Combines the advantages of centralized and distributed	High precision and flexibility	The structure is complex and the design is difficult

In summary, as shown in Table 2, multisensor cooperation benefits obvious structures and can make sense of different sensors with greater accuracy and reliability, but there are also problems, such as complex calculations, high real-time demand, and greater influence on the sensor being out of order. Future research may include an optimal fusion algorithm to reduce calculation pressure, improve the system real-time response speed, strengthen sensor fault detection and fault tolerance, explore more efficient methods of multisensor collaborative control, further improve the intelligence level of the automatic driving system, and increase security.

2.4 Advantages and Challenges of Multisensor Cooperation

In modern autonomous driving technology, multisensor collaboration is important (Hu et al., 2025). It integrates the data of multiple sensors to make the vehicle perceive the surrounding environment comprehensively and accurately. With multisensor cooperation, vehicles can better utilize the strengths of different sensors. Cameras can capture rich detailed information, radar is good at detecting distant objects, and lidar can provide high-precision three-dimensional data. Given these advantages, vehicles can accurately identify and locate objects such as obstacles, road signs, and pedestrians even in complex and changing environments. Multisensor collaboration can also compensate for the shortcomings of a single sensor. Some sensors have blind angles of view, some are susceptible to weather, and some are affected by electromagnetic interference.

For the three listed in the chart of advantages, multisensor cooperation also has many problems to solve. Sensor data fusion is very complex and needs to address the problems of data synchronization, data matching and information duplication to ensure that the fusion result is accurate and fast. The data characteristics of different sensors, data formats, sampling speeds, and measurement ranges differ, which makes data fusion more difficult. Multisensor cooperative systems need to find ways to efficiently use computing resources while reducing communication latency so that they can maintain good performance even with limited resources.

Table 3: Advantages and challenges of multisensor cooperation

Advantages	The Challenge
Improving perceptual precision	Data fusion is difficult
Enhancing environmental adaptability	Difficult synchronization between sensors
Provide redundant information	Increased system complexity
Expanding sensing range	Higher cost

As shown in Table 3, solving these problems may be in the next few directions: developing more efficient data fusion algorithms, designing more flexible sensor network structures, or exploring new sensor technologies. Through these explorations, the role of multisensor cooperation in autonomous driving will become more prominent, which can push the technology further.

3. Multisensor Data Fusion Technology

3.1 Overview of Data Fusion Technology

Data fusion technology involves multilevel and multidimensional processing of information. By integrating different sources of data, accurate, comprehensive and timely target attributes and status information are finally obtained. A single sensor can provide limited information, cover a small number of information types and may have errors. To solve these problems, multisensor information fusion technology has been gradually developed. Using this technology to process the data of multiple sensors synthetically to make an accurate judgment of the situation has become an important direction of future development (Wu et al., 2022).

Research on multisensor information fusion technology involves four main aspects, namely, the fusion model, the fusion algorithm, the fusion system and the specific application. There are three main types of fusion models: centralized, distributed and hybrid. In centralized fusion, all sensor data are transmitted to a central processor for processing. In this way, the computing resources are centralized for convenient management and control, but the communication pressure is large, and the computing power of the central processor is high. In distributed fusion, each sensor processor processes the data by itself and then transmits the results to the central processor for fusion. This method has low communication pressure and low requirements for the central processor; however, the computing resources are scattered, and management and control are difficult. Hybrid fusion combines the characteristics of the former two methods, which can make full use of computing resources and reduce the burden of communication, but it is more complex to implement (Wu et al., 2022).

The application of multisensor information fusion technology is very extensive. In intelligent traffic, intelligent medical, intelligent agriculture and intelligent cities, and other fields, as information technology advances, the technology will also play a role in the field of increasing convenience (Wu et al., 2022).

3.2 Common Data Fusion Methods

Table 4: Common data fusion methods

Method Names	Principle	Characteristics	Application scenarios
Weighted average method	The corresponding weight was given according to the reliability of each sensor data, and the weighted sum of the data was performed	The calculation is simple, and it is suitable for the case that the data have a linear relationship	The environment is relatively stable, and the accuracy of the sensor is relatively consistent
Kalman filter method	Using the system state equation and the observation equation, the system state is estimated by prediction and correction	It can effectively deal with the noise interference in the dynamic system and has good real-time performance	Vehicle motion state estimation, target tracking and other scenarios
Bayesian estimation method	Based on Bayes' theorem, the posterior probability is updated by combining the prior probability and the observed data	It can make full use of the prior information and deal with the uncertainty effectively	Target recognition, environmental perception and other scenarios, especially when there are many uncertain factors
D-S evidence theory	Represent the degree of belief in different propositions by a combination of evidence	It can deal with uncertain and imprecise information, and has a good ability to deal with conflict evidence	Multisource information fusion, target recognition in complex environment and other scenarios

Table 4 systematically combines the core information of four common data fusion methods and clearly presents the principles, characteristics and application scenarios of each method. Among them, the weighted average method “according to the reliability of empowerment sum” as the core, with the advantages of simple calculation, is suitable for environmental stability and consistent sensor precision static/quasi static scenes. The Kalman filter method is based on the prediction-update mechanism of dynamic recursion, which can effectively address noise interference and achieve good real-time performance in dynamic system scenarios such as vehicle motion estimation and target tracking. The Bayesian estimation method relies on the Bayesian theorem, quantifies uncertainty by fusing prior probability and observed data, and provides a reliable decision-making basis for target recognition, environmental perception and other scenes with multiple uncertain factors. D-S evidence theory can flexibly address uncertain, imprecise and conflicting information by means of evidence combination and a belief function, which is suitable for complex scenarios such as multisource information fusion and target recognition in complex environments. The table not only clarifies the applicable boundaries and core advantages of each method but also provides an intuitive and clear reference for the selection of data fusion methods in different scenarios through structural comparison, which lays a method’s cognitive foundation for the subsequent application and research of related technologies.

3.3 Limitations of Data Fusion Technology

Data fusion techniques currently have several obvious limitations, which manifest themselves in several ways (An et al., 2022). Data heterogeneity is a major challenge in the process of data fusion. The data generated by different sensors or data sources may have different formats, structures and semantics, which requires that the fusion algorithm can address these differences and represent the data uniformly (Du, 2024). Data quality inconsistency is also a major problem. Sensors may be affected by environmental interference, hardware failure, signal loss and other factors to produce erroneous or incomplete data, which directly affects the accuracy and reliability (Li, 2024) of the fusion results. The real-time requirement of data fusion cannot be ignored. In real-time systems such as autonomous driving, data fusion needs to be completed in a short time to ensure the timely response of the system. However, complex data processing and algorithms usually require long calculation times (Fei et al., 2019). Insufficient data fusion algorithm robustness and adaptability are also important limitations, as environmental conditions and sensor features change in actual applications, and algorithms need to adapt to these changes and maintain stable performance (Alaba & Ball, 2023). Privacy and security issues in the process of data fusion are becoming increasingly important. In multisensor or multisource data fusion, protecting personal privacy and data security and avoiding information leakage are important issues that need to be solved urgently. These limitations not only reflect the current challenges of data fusion technology but also point out an improvement direction (Yuan et al., 2024) for subsequent research.

4. Application of Multisensor Collaboration in Autonomous Driving

4.1 Application of Multisensor Collaboration in the Perception Layer

In the development process of autonomous driving technology, multisensor collaboration in the perception layer is an important support point (Du, 2024). The autonomous driving system integrates the information collected by different sensors, such as cameras, lidar, millimeter-wave radar, ultrasound, GPS, IMU, and V2X, to sense the surrounding environment more comprehensively and accurately. Multisensor fusion sensing technology (MSFP) can improve the external perception ability of a system and compensate for the limitations and uncertainties of a single sensor (Yuan et al., 2024). This technology has been applied in many fields, such as fault detection, remote sensing, and human health monitoring. It has been used in robotics systems, human–computer interactions, target recognition and tracking, simultaneous localization and mapping (SLAM), and advanced driver assistance systems (ADASs).

In autonomous driving scenarios, multisensor cooperation is used mainly for multitarget tracking and environment reconstruction. By establishing a motion model, the associated data information accurately perceives the external environment of the location of the object, the speed and motion trajectory. Multisensor fusion perception can also play a role in partially observable complex environments such as urban traffic. After multiple sources of cues are integrated, the ability of the autonomous driving system to address complex scenes becomes stronger, and the adaptability and interpretability are improved.

At present, there are still challenges to overcome in multisensor collaboration at the perception layer. There is noise and uncertainty at the data level, high algorithm complexity and high computational cost at the model level, and real-time and reliability requirements should be considered at the application level. To solve these problems, future research can start from several aspects, explore more effective fusion strategies, develop more robust algorithm models, optimize calculation methods to improve efficiency, and improve sensor technology to enhance reliability. With the continuous optimization of these aspects, multisensor collaboration in the perception layer will provide more powerful support for the development of autonomous driving technology.

4.2 Application of Multisensor Collaboration in the Decision-Making Layer

In the decision-making process of autonomous driving, the application of multisensor cooperation is mainly data fusion and information processing. In data fusion, the Kalman filter, particle filter, neural network and other algorithms are used to integrate the data from different sensors to obtain a unified environment perception result. Another important application of multisensor cooperation at the decision-making level is multitarget tracking and prediction. By fusing the data from different sensors, the decision system can track the trajectory of multiple dynamic targets more accurately and predict their future states to make decisions about avoiding or adjusting driving strategies in advance.

There are also some problems in the application of multisensor cooperation at the decision level, such as the complexity of the data fusion algorithm, the difficulty of time synchronization between sensors, and the processing of data redundancy and conflict. Future research can consider several aspects: the optimal fusion algorithm, real-time and calculation efficiency, the development of a more intelligent sensor cooperation mechanism to enhance the adaptive ability of the system, and the exploration of decision-making models based on artificial intelligence to further improve the level of decision-making intelligence. With the continuous innovation and optimization of technology, the application of multisensor collaboration at the decision-making level will be increasingly mature and efficient, which will provide more solid support for the safety and reliability of autonomous driving systems.

4.3 Application of Multisensor Collaboration at the Executive Level

In autonomous driving, multisensor cooperation in the execution layer is particularly critical (Wang et al., 2024). This approach provides the system with a more complete view of its surroundings. In complex driving situations, the use of only one sensor can miss important information. By integrating information from different sensors, the system can be more comprehensive to "see" the surrounding environment. For example, cameras can collect information about traffic signs and lights, and radar can measure the distance and speed of surrounding vehicles and obstacles. By combining this information, the executive layer can better understand the surrounding situation and make safer operational decisions.

Another benefit of having multiple sensors working together is that they increase the speed of execution-level reactions. Fast reaction times are important for autonomous driving systems because slow reactions can cause serious crashes. By integrating information from multiple sensors, the system can "see" its surroundings and process information more quickly. For example, cameras can send back information about traffic signs and lights in a timely manner, and radar can quickly measure the distance and speed of surrounding vehicles and obstacles. By combining this information, the executive layer can make operational decisions faster and control the vehicle in time.

However, there are some difficulties in multisensor cooperation in the execution layer. A is produced by different sensor data formats, and the communication protocols used also differ, increasing the complexity of information fusion. Second, the sensors themselves produce noise and may have errors in their measurements, which can affect the accuracy of the fused information. Therefore, more effective data fusion algorithms should be studied to solve these problems. In addition, as more sensors are used, the demand for computing and communication resources increases, so it is necessary to design more efficient computing and communication frameworks to ensure the cooperative work of multiple sensors.

In the future, multisensor cooperative work at the execution level will continue to develop. With the continuous progress of sensor and computing technology, multisensor cooperative work will be more efficient and accurate. Coupled with the application of artificial intelligence technology, multiple sensors working together can provide a deeper understanding of the surrounding environment and make more informed operational decisions. These advances could improve the safety and stability of autonomous driving systems and push the entire technology forward.

4.4 Application Case Study

From the perspective of the actual application of autonomous driving technology, the case of multisensor cooperative work can reflect its role in enhancing system performance and ensuring safety. Taking Tesla's autopilot system as an example, it combines data collected by cameras, radar, and ultrasonic sensors to provide a more comprehensive understanding of the vehicle's surroundings (Zou, 2022). The camera can take high-definition pictures to provide rich visual details. The radar is not affected by bad weather and can overcome the shortcomings of the camera in terms of rain and snow. The ultrasonic sensor is sensitive to nearby objects and suitable for detecting close obstacles. For both sunny and rainy days, all kinds of complex road conditions can operate stably.

Another good example is Google's Waymo self-driving system, which allows lidar, cameras, and millimeter wave radar to work together. Lidar can perform high-precision three-dimensional scans to create detailed three-dimensional maps of the surrounding environment, the camera can capture color and texture so that the system can see more clearly, and millimeter wave radar is sensitive to high-speed moving objects and suitable for long-distance detection. The data collected by these sensors are deeply fused through advanced algorithms. The Waymo system can more accurately analyse complex traffic conditions and judge possible risks in advance, making driving safer and more reliable. The Bosch autopilot scheme also embodies the value of multiple sensors at the same time via multiple cameras, radar and laser radar through multiple levels of awareness and comprehensive monitoring vehicles around the data fusion technology. In particular, in complex urban road conditions, a variety of sensors can more accurately identify pedestrians, bicycles and other vehicles and avoid brake responses in time, which can significantly reduce the possibility of accidents.

These cases highlight the advantages of multisensor collaboration but also present several problems, such as the fact that sensor data synchronization and processing speed are not fast enough, the data fusion algorithm in complex environments needs to be improved, and the cost and later maintenance of sensors are also issues to consider. Future research can focus on improving the real-time data processing ability, optimizing the fusion algorithm, finding ways to reduce the cost of sensors, and exploring more efficient maintenance methods, which can make autonomous driving technology more mature and widely used.

5. Conclusion

In recent years, autonomous driving technology based on multisensor collaboration has developed rapidly, and a variety of mainstream solutions have been developed with marked effects. Multimodal sensing schemes integrate lidar, cameras and other advantages to improve perception ability and robustness; however, data processing is complex, and real-time performance is difficult to guarantee. The fusion methods based on deep learning achieve high-precision perception and decision-making with strong feature extraction and learning capabilities but rely on massive amounts of data and lack model generalizability ability. The distributed collaboration architecture adopts a decentralized mechanism to improve system reliability and response speed, but the communication protocol is complex, and the collaboration mechanism needs to be optimized. The technology based on filtering theory is based on classical algorithms to ensure data accuracy and stability, but the algorithm adaptability needs to be improved in complex environments.

These approaches advance the field of autonomous driving, but each has limitations that reflect the urgency of future research. For example, how to effectively reduce the data processing complexity of multimodal sensing schemes and improve the real-time performance of the system is an important direction for future research. In view of the shortcomings of deep learning methods, exploring more efficient data utilization strategies and methods to enhance the generalization ability of the model may be the key to overcoming this bottleneck. The communication of the distributed collaborative architecture needs to be optimized, the coordination mechanism needs to be designed, and the adaptive problem of filtering theory in complex environments also needs more theoretical innovations and technical breakthroughs.

In the future, autonomous driving technology based on multisensor cooperation will play an increasingly important role in the field of intelligent transportation. By optimizing the existing technical solutions and overcoming their limitations, combined with emerging technologies such as artificial intelligence and edge computing, achieving a higher level of autonomous driving systems and providing people with safer, more efficient and convenient travel experiences is promising. The interdisciplinary research method will also provide a new impetus for the development of technology and promote its application and popularization in more fields.

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The authors declare no conflict of interest.

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