The Application of Fusion of Millimeter-Wave Radar and Image Sensors in Intelligent Driving

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Abstract. In the field of intelligent driving, multi-sensor fusion has been applied to many systems. With the rapid advancement of autonomous driving technologies, environmental perception and high-precision positioning have become critical for enhancing vehicle safety and operational efficiency. The growing complexity of urban traffic scenarios further necessitates robust and redundant sensing systems to ensure reliability under diverse conditions. According to the fact that millimeter-wave radar and image sensors are widely equipped on vehicles, this essay summarizes the main concepts of intelligent driving and multi-sensor fusion, while analyzing the factor graph optimization algorithm and fusion network model applied to the fusion positioning of millimeter-wave radar and image sensor, with discussions on the application of multi-sensor fusion in achieving precise positioning functions for auxiliary intelligent driving systems. At the same time, the essay also discusses the shortcomings of intelligent driving systems used in contemporary vehicles. Therefore, researching the fusion technology of millimeter-wave radar and image sensors holds significant theoretical value and practical importance for enhancing environmental perception accuracy and driving safety.

Keywords: Multi-sensor fusion; Intelligent driving; Millimeter-wave radar; Image sensors.

1. Introduction

Intelligent Driving is the mainstream of the contemporary driving system study, while the skills now can not realize the Full Autonomous Driving of the Intelligent Driving level 5 [1]. The main obstacle is that a single sensor can cause huge errors with less effective data when facing a complex environment, which does not satisfy the demand of Intelligent Driving. The single sensors are usually influenced by the environment; for example, image sensors have a better collection effect on stationary objects, but they may be affected by bad weather or other low-visibility environments, making it impossible to accurately collect environmental data. Meanwhile, although Millimeter-Wave radar is not hindered by bad weather and can collect and reflect exact statistics of high-speed objects, it cannot return Z-axis data and has a poor detection effect on objects with weak reflection. Although sensor arrays can be used to solve the above problems, they will significantly increase the cost and volume, which is not conducive to application in vehicle-themed intelligent driving systems.

The fusion of multiple sensors enables the integration of data feedback from different sensors, allowing intelligent driving carriers to obtain more comprehensive data at lower cost and with smaller volume when facing complex environments, thereby enhancing the reliability and robustness of the system. Thus, combining intelligent driving with multiple sensors is a natural course of action. In modern society, image sensors and millimeter-wave radars have been widely applied in various aspects of vehicles and are also the main sensors in intelligent driving systems. Meanwhile, wheeled vehicles are the main carriers in intelligent driving. Through the fusion of millimeter-wave radars and image sensors, wheeled vehicles can more accurately analyze environmental data when using intelligent driving, and provide reminders or warnings to drivers when necessary, ensuring driving safety and convenience.

Current research mainly focuses on intelligent driving itself, the application of multi-sensor fusion in positioning, and related algorithms for multi-sensor fusion, such as using factor graph algorithms to enhance positioning accuracy. Based on the above research, this paper explores

whether the fusion of image sensors and millimeter-wave radars can provide more accurate environmental data and positioning information for intelligent driving systems. This article discusses the application of multi-sensor fusion in intelligent driving, including its basic requirements, multi-sensor fusion methods and their practical applications. It focuses on introducing the basic principles and common application types of two types of sensors: millimeter-wave radar and image sensors. It also discusses the fusion requirements of the two and their applications in intelligent driving, and makes prospects for their future development

2. The Overview of the Intelligent Driving and Multi-sensor Fusion

2.1. Intelligent Driving

Intelligent driving is a technology that utilizes advanced sensors, controllers, actuators, and other devices to achieve autonomous vehicle navigation and driving through the application of artificial intelligence and machine learning algorithms. The five main core functions of intelligent driving technology are: lane keeping assistance, automatic cruise control, traffic sign recognition, automatic emergency braking, and automatic parking [1].

Among them, the important application scenarios of lane-assisted driving or lane-keeping assistance systems are that when the driver's inattention causes the vehicle to deviate from the original route, the system can remind the driver to return to the original route or actively return to the current route. Automatic cruise control is a system that enables the vehicle to autonomously adjust the cruise speed during long-distance driving to reduce the driver's driving pressure. Traffic sign recognition is the active identification of traffic signs along the road by vehicles, helping drivers understand the traffic conditions along the way. Emergency braking technology is indispensable in ensuring driver safety. This system enables vehicles to give early warnings and avoid or brake in case of emergencies, ensuring the safety of drivers' lives. Automatic parking enables vehicles to actively seek parking Spaces and assist drivers in parking their vehicles in narrow Spaces [1].

Intelligent driving systems represent the mainstream driving direction in the future. Realizing and using the internationally defined L5 fully autonomous driving system is an indispensable function for future vehicles. The realization of intelligent driving is deeply dependent on the computing performance of the on-board computer and the amount of effective data fed back by vehicle sensors Generally speaking, the more valid data there is, the more accurate the decisions made by the controller will be, the more precise the perception and decision-making of the outside world will be, and the higher the closed-loop degree of intelligent driving will be, until fully autonomous driving is achieved.

2.2. Multi-sensor Fusion

Multi-sensor Fusion (MSF) is an information processing process that uses computer technology to automatically analyze and synthesize information and data from multiple sensors or multiple sources according to certain criteria to complete the required decision-making and estimation. The basic principle is to use different sensors to complement and fuse different information collected by the observation target, produce a consistent interpretation of the observation target, and improve the overall stability and robustness of the system. Using the multi-sensor fusion method for the same number of sensors can significantly increase the amount of valid data collected by the system compared to working separately. For example, in a harsh environment, taking the image sensor and millimeter-wave radar as an example, the image sensor may not be able to obtain data that can be directly identified and used by the system due to the influence of the environment, and only one sensor of the millimeter-wave radar feeds back valid data, and the use of multi-sensor fusion can preprocess the data returned by the image sensor to obtain the available part so that the system can obtain more valid data. At the same time, the more sensors used, the more effective the data for multi-sensor fusion feedback, and the more accurate the decisions made by the system. The core of

multi-sensor fusion is that sensors can return data for the system to fuse, making fuller use of the data. In order to obtain higher data accuracy and more effective data to improve system processing speed and system decision accuracy, a common idea is to use sensor arrays to obtain more data and compensate for the inherent defects of sensors. For example, common millimeter-wave radar arrays can collect different data in multiple directions, making up for their inability to collect z-axis coordinates.

However, more sensors bring more under-dealing data, higher cost and more pressure on the system. So, promoting deeper data fusion when the system processor cannot be replaced or there are strict requirements for the overall volume of the system is also a good way to improve the efficiency, accuracy and robustness of multi-sensor fusion Data fusion is divided into three levels: The first is data layer fusion: directly integrating data from a single sensor to retain the maximum original information. It requires high-precision synchronization and calibration, has a large amount of data and a complex processing procedure, and is suitable for scenarios with a single sensor and strong data correlation. The second is featuring layer fusion: extracting features from each sensor, fusing them for target recognition and classification. It can reduce the amount of data but relies on the accuracy of feature extraction by sensors, and is suitable for environments that require a comprehensive judgment of multiple features. Finally, there is the decision-making level fusion: each sensor makes independent decisions, fuses the results, and reaches a final consistent conclusion. It has high flexibility and a low degree of dependence on sensor accuracy, but it may introduce biases due to the limitations of a single sensor, and is suitable for scenarios with independent functions and clear decision-making logic This technology, through hierarchical collaboration, makes up for the shortcomings of a single sensor and provides high-precision environmental perception and decision support for complex systems such as autonomous driving Nowadays, the commonly used method is data layer fusion. In some scenarios, feature layer fusion may be employed. However, multi-sensor fusion should ultimately achieve decision fusion to ensure that the system can make more accurate decisions, thereby enhancing the system's accuracy and stability [2].

2.3. Millimeter-wave Radar

Millimeter-wave radar refers to radar operating in the millimeter-wave frequency band. Millimeter is an electromagnetic wave with a working wavelength range of 1 to 10mm, corresponding to a frequency range of 30 to 300 GHZ. The advantages of millimeter-wave radar are its small size and ability to operate normally in both rainy and snowy weather [3]. In practical applications, based on the function of millimeter-wave radar that can effectively identify the speed and direction of moving objects, it is usually utilized in the field of intelligent driving for vehicle speed detection and movement prediction of objects outside the vehicle. Although millimeter-wave radar cannot measure the Z-axis, in normal driving environments, vehicles can move approximately in the same plane. Using millimeter-wave radar can meet the actual needs.

2.4. Image Sensor

The image sensor is a type of sensor that uses the photoelectric conversion function of optoelectronic devices to convert the light image on the photosensitive surface into an electrical signal that is proportional to the light image. The common types of image sensors are various cameras, which are often used in practical applications to directly collect environmental data At the same time, as image sensors are mainly composed of various cameras, they have a high accuracy in data collection for static objects or observed objects at a certain moment, and can collect the features of the observed targets relatively clearly. They are the most commonly used type of modern sensors.

3. Application of Image Sensor and Millimeter-Wave Radar Fusion

3.1. The Significance of Image Sensor and Millimeter-Wave Radar Fusion

In today's scientific and technological research and development, multi-sensor fusion has become the mainstream method to improve system decision-making accuracy. Compared with traditional single sensors, multi-sensor fusion can use data collected by multiple sensors at the same time and conduct centralized analysis, which is much smaller than the errors and limitations caused by the feedback data of multiple sensors alone. In practical applications, image sensor and millimeter-wave radar fusion is a low-cost but highly accurate solution. At the same time, in the existing common schemes, the single sensor detection method of image sensors mainly relies on the real-time environmental image information collected by sensors such as cameras, which are perceived and recognized by the central controller, so as to achieve all-around control of the surrounding environment and autonomous driving functions. This method has the characteristics of strong real-time performance and good adaptability [4], but it is more susceptible to environmental influences, such as the image sensor may not perform well in rain, snow or fog weather, and for dynamic objects, such as high-speed objects such as driving, it may not be observable or the sensor returns little or no effective data due to the limitation of camera exposure time. The detection method based on millimeter-wave radar can ignore the adverse effects of the environment and is small and easy to install on the vehicle. However, millimeter-wave radar can only observe planes and has poor detection of static objects or objects with inobvious reflections, such as pedestrians [3]. However, the detection of this type of low-speed object happens to be the detection advantage of image sensors. Thus, the fusion of image sensors and millimeter-wave radar is a good solution that can deal with harsh environments and high accuracy requirements in practice. At the same time, the use of image sensors and millimeter-wave radar fusion can also greatly increase the perception of the vehicle body, and perception ability is the key to vehicle safety [5].

3.2. Basic Conditions for the Fusion of the Image Sensor and the Millimeter-Wave Radar

Based on the existing vehicle structure, most vehicles are equipped with image sensors and millimeter-wave radars to assist drivers in driving or for parking. Intelligent driving of vehicles can be achieved without extensive structural changes, and the accuracy and decision-making of intelligent driving of vehicles can be significantly improved at a relatively low cost. At the same time, the detection method of millimeter-wave radar is a wave, which does not conflict with the camera technology used in image sensor detection. There will be no redundancy of the system caused by overlapping sensor feedback data within the system. Moreover, due to the significant differences in their detection methods, the same object can be observed from different angles. The advantages and disadvantages of the two can complement each other. Image sensors provide high-precision data, while millimeter-wave radars make up for the poor performance of image sensors in harsh or complex environments It can provide the system with more precise data on observed objects, improving the accuracy of system decision-making while also preventing traffic accidents caused by system misjudgment and reducing personnel and social losses due to accidental errors In terms of data processing, millimeter-wave radar and image sensors are often used simultaneously. Therefore, they are designed in a move that can be integrated into the same system during the design stage, significantly reducing the time and effort that researchers need to spend integrating the two into the same system.

3.3. Method of Image Sensor and Millimeter-Wave Radar Fusion

Multi-sensor fusion mainly superimposes the data feedback from different sensors to enhance the resolution ability of the system. The main problem is that noise brings errors in data superposition and fusion, and there are problems of superimposing useless data on each other or useless data on top of useful data. The main solution is to filter noise using filters [6]. The fusion of image sensors and millimeter-wave radar is mainly used in vehicle positioning, and the existing methods are

mainly Kalman filtering, particle filtering, and graph optimization methods. The above methods have their own problems, so the factor graph optimization algorithm was invented to solve the problem. The factor graph optimization algorithm uses IMU pre-integration factor, LIDAR odometer factor, GNSS-RTK factor, and loop detection factor to improve accuracy, and it does show its advantages in related experiments, which can bring more accurate positioning to the system as a whole and lay a good foundation for the subsequent related work of intelligent driving based on precise positioning [7]. Another approach is to converge the network model. For the feedback data of different sensors, firstly, the targets detected by the camera and millimeter-wave radar are obtained respectively, and their features are extracted by using modality-specific coding. The multimodal features are then transformed into a unified BEV representation while retaining their respective geometric and semantic information. A convolution-based BEV encoder is then applied to the unified BEV features to mitigate local biases between different features; Finally, the object detection head is added for object detection and the vehicle target on the road is output. This method can be used to construct highly accurate maps and target detection models. All of these algorithms can achieve the integration of image sensors and millimeter-wave radars and can be directly utilized by intelligent driving systems.

4. The Application of Image Sensor and Millimeter-Wave Radar Fusion in Intelligent Driving

4.1. Basic Application Principles

Target recognition and self-positioning are crucial in intelligent driving systems. Global Positioning System (GPS) and Inertial Measurement Unit (IMU) provide inertial information and global location information for autonomous vehicles to determine their own position [8], so that the vehicle can update its position in real time in high-precision maps (HPM). However, due to certain errors in satellite positioning sensors, there is a certain circular error in the positioning data, which cannot meet the actual needs, so end recognition and inertial guidance have become particularly important. As mentioned above, millimeter-wave radar can identify people and vehicles, and image sensors can accurately identify the environment, which are also the main technical means for vehicles to identify external targets. Before the use of technology, the system will automatically enable the database that collects the surrounding environment data and maps, and narrow the search scope according to the coordinate data feedback from the satellite, and then use image sensors and millimeter-wave radar to quickly identify environmental characteristics, compare with the database, and make position corrections to know its own location. It can be seen that in the most basic positioning system, image sensors and millimeter-wave radar are important parts of its precise positioning. At the same time, in actual road traffic, road conditions will not be static or completely covered by preset response plans, so intelligent driving systems need to adapt flexibly. But no matter how complex the road conditions are, the system needs clear and accurate external data for decision-making, and this is the sensor's job to collect the data. As the most common sensor modules on vehicles, image sensors and millimeter-wave radar can not only identify the surrounding environment, but also accurately identify pedestrians and oncoming vehicles on the road. The fusion of the two not only improves the accuracy and effectiveness of data collection but also greatly strengthens the robustness and stability of the system.

4.2. Multi-sensor Mapping and End-View Positioning are Applied

Mapping and positioning are the keys for intelligent driving systems to achieve precise terminal positioning. In practice, LVI-SAM-Stereo is a common method. Based on LVI-SAM-Stereo, two subsystems are constructed. That is, feature points are extracted respectively by using image sensors and millimeter-wave radars [9]. Meanwhile, the pre-integration of IMU is taken as the initial position. Then, position collection is carried out and a map is constructed. After proofreading with

database data, the determined position coordinates are generated to eliminate the circular error caused by satellite positioning. At the same time, in terms of achieving end-view positioning, ORB technology can be utilized to quickly extract image features and pair them with the image library for recognition. By rapidly capturing key points, the extraction of image features is completed, supplemented by machine learning to improve accuracy. The key information of the image is obtained and then compared with the database to accelerate the comparison speed. Finally, the position is corrected by using the database for positioning. Realize the positioning of the end view [10].

4.3. Practical Application

Most of the existing automotive enterprises have carried out a series of research and development on intelligent driving systems. Many have developed driving assistance systems with considerable stability and accuracy, such as Volvo's emergency avoidance system. After the introduction of assisted driving systems, some enterprises and research institutes have also launched some unmanned vehicles to assist urban construction and facilitate residents' lives, such as the unmanned food delivery vehicles in Wuhan Meanwhile, the existing technology enables vehicles to drive autonomously when the traffic conditions are relatively clear, or to relieve the driver of some driving pressure. Meanwhile, unmanned vehicles can achieve unmanned driving functions in relatively simple scenarios according to the planned routes in the field of agricultural machinery, intelligent driving technology is more widely applied. With the support of science and technology, various intelligent farm tools equipped with intelligent driving systems have been used in agricultural production. This not only increases the intelligence of agriculture but also significantly boosts crop yields and improves crop quality, reducing the labor burden on farmers [6]. For instance, intelligent unmanned seeders and unmanned pesticide sprayers are adopted in farmlands.

4.4. Existing deficiencies

Although existing automotive enterprises and some research institutes have claimed that they have achieved fully driverless systems, there are still many traffic accidents in society caused by the malfunction of driverless systems, and driverless vehicles also frequently break down, which continuously reduces the public's public property and people's confidence in driverless technology, ultimately leading to the ban on driverless systems The core key to intelligent driving or driverless systems lies in navigation and positioning as well as system decision-making [1]. The existing systems cannot achieve long-term error-free operation. For instance, the data collection error increases due to the overheating of sensors after long-term operation, and the system error may lead to system decision-making mistakes, thereby causing traffic accidents. Similarly, errors in satellite positioning may also cause errors in road recognition in the system, leading to traffic accidents. Meanwhile, existing traffic simulations or short-term road traffic experiments cannot fully restore the complexity of real traffic, resulting in the system being unable to independently handle highly complex road traffic situations and still requiring human intervention and control.

5. Conclusion

The fusion of image sensors and millimeter-wave radars can provide more accurate data for intelligent driving systems, supporting them in making more precise decisions. Existing technologies can enable systems to utilize existing sensors to complete higher-precision data collection and more accurate decision-making through multi-sensor fusion The core of multi-sensor fusion: The next research step should focus on the fusion of multiple sensors at the decision-making level, and develop an intelligent driving system that maintains the original steady-state error even after long-term operation, as well as enhance the fidelity of laboratory traffic environment simulation The fusion of image sensors and millimeter-wave radars in multi-sensor fusion is undoubtedly a technology that can enhance the stability and robustness of intelligent driving

systems. While improving the positioning accuracy of the system, it also significantly enhances the system's ability to perceive the outside world, ensuring that the system has a certain degree of external perception to support it in making emergency decisions.

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