Overview of Multi-sensor fusion in Autonomous Vehicles

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Abstract

In this article, we give a brief overview of sensors and sensor fusion in autonomous vehicles field. We focus on sensor fusion of key sensors in autonomous vehicles: camera, radar and lidar. This article will introduce the latest sensor fusion algorithms developments in this field. The results show that adding more sensors to the sensor fusion system can improve the performance and robustness of the system. In addition, the multi-sensor fusion of GNSS and IMU data are vital for positioning and mapping, which is a solution to the problem of the real-time requirements of automatic driving. Sensor fusion plays a vital role in autonomous driving systems, so it is one of the fastest growing areas in the field of autonomous vehicles.

1 Introduction

Intelligent net-connected vehicle mainly uses modern sensors, network communication, intelligent computing system, automatic control and other technologies. The key components of autonomous vehicles are the sensors. Intelligent net-connected vehicle is the organic integration of multi sensors and connected to the Internet, not only carries the advanced on-board sensors to help the vehicle to achieve the advanced environmental awareness [1], high-precision map to realize vehicle routing planning, vehicle control algorithm and actuator device to realize accurate control of vehicles [2]. Moreover, it realizes the exchange and mutual sharing of intelligent information between cars, people, roads, and back-end systems to realize safe, comfortable and efficient driving. It is a new generation of cars that can eventually replace people to operate [3]. Nowadays, a growing number of start-ups and companies around the world are committed to delivering solutions towards SAE Level 5 functionality, which will completely change the way people use mobile solutions in the near future [4]. Autonomous driving system is shown in Figure 1.

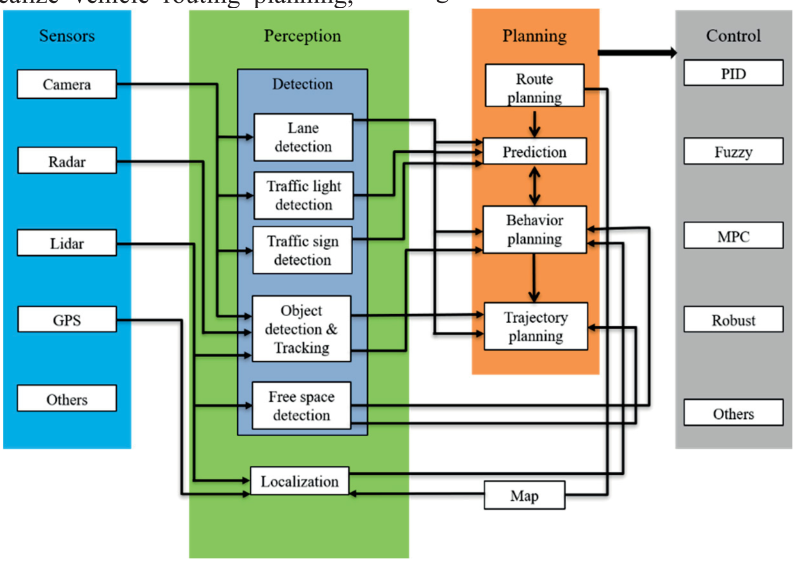

Figure 1 Autonomous driving system.

2 Principle of multi-sensor fusion

In 1997, Hall and Llinas gave a general introduction to multi-sensor data fusion [5]. Another in-depth review paper on multiple sensors data fusion techniques was published in 1998 [6]. Sensor fusion is a method of combining data from different data sources to generate coherent information. The basic principle of multi-sensor information fusion technology is like the process of comprehensive information processing by the human brain [7]. Various sensors are processed for multi-level and multi-space information complementary and optimized combination processing, and finally, a consistent interpretation of the observation environment is produced. Through multi-level and multi-space information complementation and optimized combination processing of various sensors, a consistent interpretation of the observation environment is finally produced. In this process, it is necessary to make full use of multi-source data for reasonable control and utilization [8]. The ultimate goal of information fusion is to derive more useful information based on the separated observation information obtained by the separation of various sensors, through the multi-level and multi-directional combination of data [9]. In general, the sensors used in studies mainly include lidar,camera,ultrasonic,LTE-V2X and 5G-V2X.Table 1 below summarized the advantages and disadvantages of the different types of sensors and the detection range, which shows that different sensors have apparent differences in operating characteristics. Another statistic of the characteristics, advantages, disadvantages, and applicable scenarios for each sensor is given in Figure 2.

Multi-sensor fusion not only takes advantage of the collaborative work of multiple sensors, but also comprehensively processes data from other information sources to improve the intelligence of the entire sensor system [10]. Post-fusion algorithm refers to the definition that each sensor independently processes the generated target data, and each sensor has its own independent perception [11]. After all the sensors complete the target data generation, the central processor performs data fusion. Front fusion algorithm refers to the definition that there is only one perceptual algorithm [12]. Perceive the fused multi-dimensional integrated data. The data is fused together in the original layer. The fused data is like a super sensor, and this sensor not only has the ability to see infrared rays, but also has the ability to see the camera or RGB and the ability to see the three-dimensional information of LiDAR. It's like a pair of super eyes [13]. On this pair of super eyes, perception algorithm is developed, and finally a result layer object is outputted.

To use the same hardware to issue the trigger acquisition command at the same time to realize the time synchronization of the acquisition and measurement of various sensors is hardware synchronization and hard synchronization[14]. To collect the same information at the same time is the process of software synchronization which includes time synchronization and space synchronization.

Table 1 Comparison of different types of sensors and technologies

Type	Advantages	Disadvantages	Maximum working distance of sensor
MMW-Radar	1) Long working distance 2) Available for radial velocity 3) Applicable for all-weather	1) Unapplicable for static objects	200m
Lidar	1) Wide field of view 2) High range and angle resolution	1) High price 2) Insufferable for bad weather	200m
Camera	1) Excellent discernibility 2) Available for color distribution	1) Heavy calculation burden 2) Light interference 3) Weather susceptible 4) Unavailable for radial velocity	250m
Ultrasonic	1) Low price	1) Low resolution 2) Inapplicable for high speed	2m
LTE-V2X	1) Long working distance	1) High latency in long distance	2km
5G-V2X	1) Ultra-high data transmission rate 2) Low latency 3) High bandwidth	1) Immature application	300m

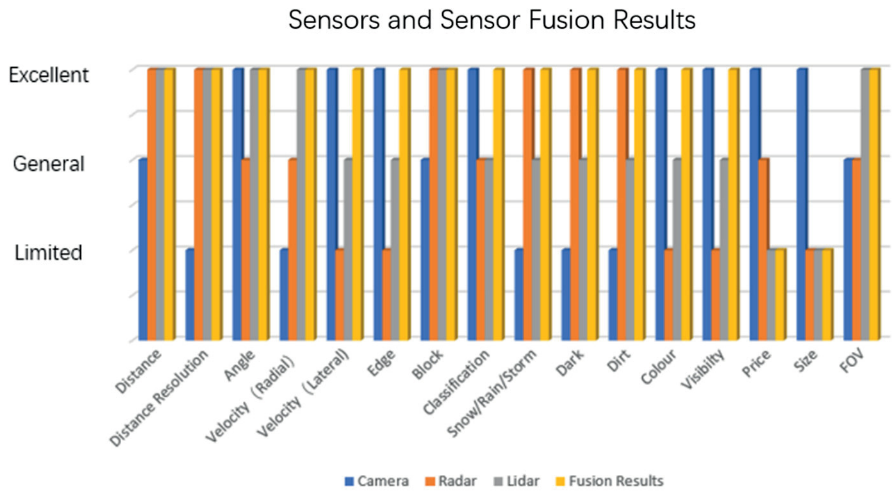

Figure 2 sensors and sensor fusion results

3 Multi-sensor fusion solution

Multi-sensor fusion schemes include fusion between lidar and real-time dynamic carrier phase differential positioning technology, fusion between lidar and IMU and other fusion algorithms. Among them, the lidar and RTK fusion algorithm has high positioning accuracy [15], and RTK positioning has no cumulative error, but RTK cannot work indoors or under severely obstructed environments, and its robustness is poor. Lidar and IMU fusion algorithms have loose coupling, tight coupling and deep coupling algorithm [16]. The loose coupling algorithm based on Kalman fusion has strong scalability and can be connected to other sensors to work at the same time, but when the IMU drifts too severely after long-term operation, the positioning accuracy becomes low [17]. The tight coupling algorithm optimizes the poses of the lidar and IMU at the same time by establishing a unified error function, with high positioning accuracy and good real-time performance [18]. Due to the low update frequency of GNSS positioning information, it cannot meet the real-time requirements of automatic driving, and the positioning signal is easily interrupted by obstacles. INS (Inertial Navigation System) is equipped with high-frequency sensors, which can provide high-precision vehicle speed, position and heading within a certain period of time, but its error will increase sharply with the accumulation of system running time[19]. Combining GNSS with INS, the high-precision positioning provided by GNSS that does not increase over time can be used to correct the cumulative positioning error of INS. At the same time, INS can solve the problem of susceptibility to GNSS scenarios [20]. By combining the advantages of the two systems, precise positioning can be obtained. If combined with map matching technology, the information provided by high-precision maps can further provide positioning accuracy [21]. To achieve the fusion of multiple positioning systems and provide positioning accuracy, it is important to design a system that fuses multiple sensor data [22].

The fusion of GNSS and IMU data is a commonly used sensor fusion technology. GNSS is a relatively accurate positioning sensor, but the update frequency of GPS is relatively low and cannot meet the calculation requirements [23]. The IMU positioning error will increase with the running time. However, the IMU is a high-frequency sensor, so it can provide stable real-time position updates in a short time. Assuming that the frequency of IMU is 1kHZ and the frequency of GPS is 10HZ, then 100 IMU data points will be used for position prediction between every two GPS updates [24], which can greatly improve the accuracy of the sensor. The data of multi-sensor fusion mainly includes the input data of GNSS, RTK, inertial navigator and special matching self-positioning [25]. After preprocessing, data registration and data fusion of these data, the speed, position and posture of the car body are outputted. The architecture of multi-sensor fusion is divided into distributed, hybrid and centralized fusion. The multi-sensor fusion architecture mainly includes combination structures such as loose coupling, tight coupling and deep coupling [26].

The principal diagram of multi-sensor fusion technology is shown in Figure 3 1) Loose coupling: GNSS provides location information to INS, which are hardware independent and can be disconnected at any time. The location information and speed information are respectively outputted to the fusion filter. 2) Tight coupling: The pseudo range and pseudo range ratio calculated by GNSS marring and carrier tracking loop are compared with the pseudo range and pseudo range ratio calculated by the inertial navigation system combining its own information and satellite ephemeris to obtain the measurement residual of pseudo range and pseudo range ratio. (3) Deep coupling: Compared with the tight coupling system, the deep coupling system adds the assistance of the INS unit to the GNSS receiver [27].

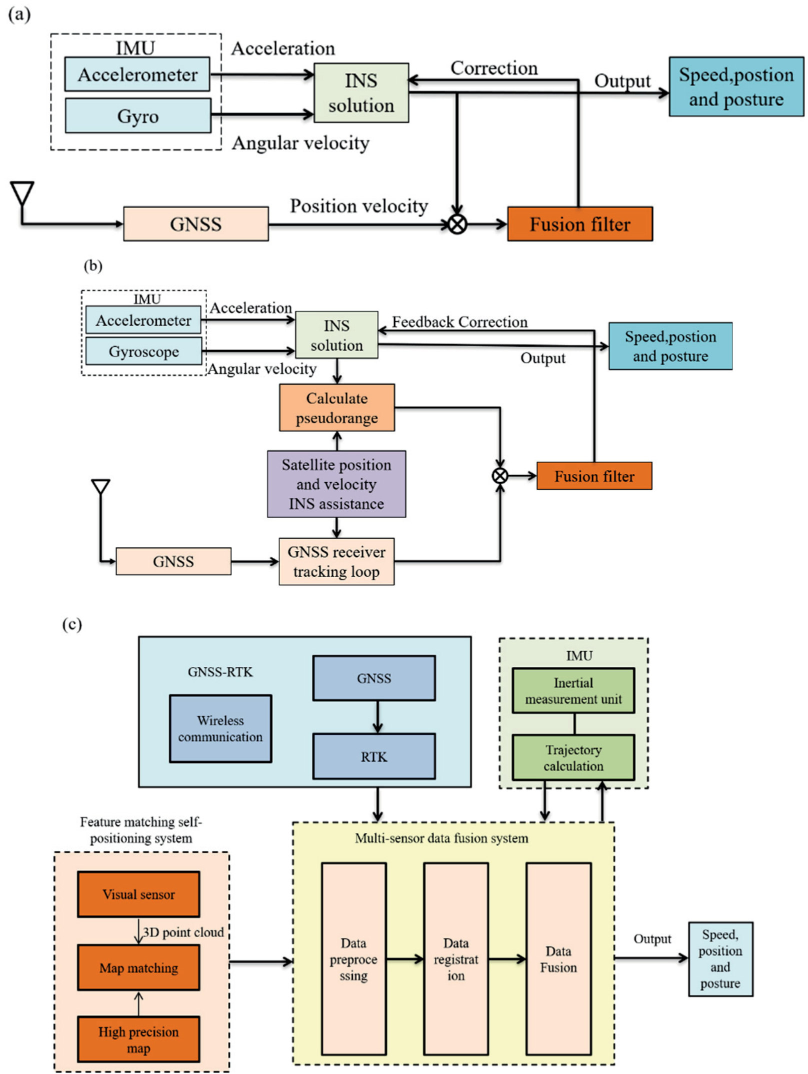

Figure 3 multi-sensor fusion system: (a)GNSS/INS Schematic diagram of loose coupling system. (b) GNSS/INS Schematic diagram of tight coupling system. (c) Schematic diagram of multi-sensor data fusion positioning process.

The Kalman filter commonly used in automatic driving is the federated Kalman filter. Federated Kalman filtering is generally divided into two steps of filtering, namely filtering based on local sensors first, and then the main filtering [28]. Other fusion algorithms are suitable for different environments and conditions [29]. The characteristics of various fusion algorithms are compared in the following Table 2:

Table 2 Comparison of the characteristics of common fusion algorithms.

Fusion algorithm	Operating environment	Fusion technology	Scope of application
Comprehensive estimation	Dynamic	Weighted average	Low-level fusion
Bayesian estimation	Static	Bayesian estimation	High-level fusion
D-S evidential reasoning	Static	Logical reasoning	High-level fusion
Kalman filter	Dynamic	System model filtering	Low-level fusion
Fuzzy logic algorithm	Static	Logical reasoning	High-level fusion
Neural network algorithm	Dynamic and static	Neuronal network	Low/High-level fusion
Expert system	Static	Logical reasoning	High-level fusion

4 Summary

(1) The dependence on the accuracy of the sensing sensor is strong. Under sudden road conditions, safety cannot be fully guaranteed, and the algorithm robustness is insufficient; the core sensor represented by lidar is extremely expensive, and the cost of vehicle modification is much higher than the cost of the entire vehicle.
(2) In order to overcome the limitations of single-vehicle automatic driving, give full play to the synergy between vehicles and smart roads, build a vehicle-road collaborative automatic driving system, realize a high degree of automation of vehicles, and reduce the cost of automatic driving.
(3) In the future, Information of vehicle group intelligence perception technology will further empower autonomous driving and help the commercialization of autonomous driving. The trend of wireless communication standards is to unify global technology and frequency bands to achieve economies of scale and achieve universal terminals and network equipment at the low-est cost.
(4) The ability of vehicles to store and process large amounts of data at high speeds, as well as to analyze and make decisions based on large amounts of historical and real-time data, also puts forward higher requirements to process the multi-sensors data. Therefore, it is necessary to introduce more powerful computing capabilities into the car and provide the car with computer-based requirements.

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