Key Sensors in Autonomous Driving Systems

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Abstract. In the past five years, intelligent driving technology has gradually matured, and autonomous driving technology has gradually moved towards the L3-L5 level, so the environmental perception system needs to continuously update its accuracy and stability. Sensors are one of the important ways to receive and transmit environmental signals, so the use and selection of sensors are particularly important. In intelligent driving systems, the monitoring and collection of environmental signals are usually carried out in the form of the joint work of multiple or multi-modal sensors. Therefore, understanding the functions and advantages and disadvantages of different sensors is of great help to people in the development of sensor fusion and intelligent driving systems. This article mainly outlines the different types of sensors used in intelligent driving, such as cameras, millimeter-wave radars, lidars, and ultrasonic sensors, as well as their advantages and disadvantages in application, the development of different sensors and the opportunities and challenges of future applications and intelligent driving, to help future generations better retrieve and develop intelligent driving systems.

Keywords: Autonomous Driving, Sensors, AI, Fusion

1 Introduction

As one of the frontier directions of the development of transportation science and technology today, autonomous driving technology is leading the evolution of transportation systems towards intelligence, unmanned operation and networking. Its core goal is to build an intelligent transportation system that can autonomously complete tasks such as path planning, obstacle avoidance, decision-making and control without human intervention. In this context, environmental perception capability has become one of the key factors that determine the performance of autonomous driving systems. Especially in complex and changeable actual traffic environments, such as urban roads, intersections, highways and other scenes, the system needs to accurately perceive a large number of environmental factors including lane lines, vehicles in front, pedestrians, traffic signs, signal lights, etc., and maintain stable and reliable operation capabilities under harsh conditions such as rain, fog, night, and snow. The core of the environmental perception module is the deployment and coordinated operation of multiple types of sensors. Through multi-dimensional and multi-scale perception of the vehicle's surrounding environment by different types of sensors, the autonomous

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driving system can achieve real-time detection of target objects, state prediction and behavior inference, and then support subsequent path planning and control decisions. Therefore, in-depth research on the types of sensors, perception capabilities, system integration methods and fusion strategies has become a key topic to promote the continuous progress of autonomous driving technology.

This review aims to comprehensively sort out the most widely used perception sensor technologies in current intelligent driving systems, conduct in-depth analysis from the aspects of perception principles, performance comparison, application scenarios, etc., and combine the latest research results and industry trends to look forward to the future development direction and integration challenges of sensor technology, providing a reference for scholars and engineers engaged in related research

2 Classification of autonomous driving sensors

To effectively realize autonomous driving, perception capability is of paramount importance, and this heavily relies on the deployment of multiple complementary sensors. Each sensor type contributes uniquely to environmental understanding—be it spatial mapping, obstacle detection, or semantic interpretation. However, no single sensor can meet all operational needs across varied and dynamic driving environments. Thus, a systematic classification and analysis of the core sensors used in intelligent driving systems is essential. The following sections will comprehensively examine key perception sensors—camera, millimeter-wave radar, LiDAR, and ultrasonic sensors—highlighting their working principles, strengths, limitations, and their roles in modern autonomous driving systems.

2.1 Camera radar

As a common and widely used type of sensor for detecting environmental information, camera radar has been widely deployed in autonomous driving systems in recent years due to its significant advantages such as low cost, convenient operation and flexible deployment. Its sensors can usually be flexibly installed at the front, rear, sides or even multiple locations inside the vehicle to cover the field of view in different directions and adapt to the needs of complex and changing traffic environments. It can be used as a forward collision warning system, lane departure warning system, traffic sign recognition system, parking assistance system, blind spot monitoring system, etc. for observation and assisted driving in autonomous driving or assisted driving [1]. The core advantage of camera radar lies not only in its low physical cost and high flexibility, but also in its powerful image acquisition and processing capabilities. Its working principle is based on the photoelectric effect, that is, the optical information in the visible light range is captured through the lens and image sensor, and the collected optical signal is converted into digital point signals in rows and columns through pixel units and output [2]. Since the camera sensor can capture RGB image information with sufficient attributes, these attributes can describe the unique identity of the object [3]. This ability is particularly critical in identifying visually significant targets such as traffic signs, pedestrians, vehicle edges, and obstacle boundaries, providing rich and accurate raw information for subsequent target detection, recognition, and classification. At the same time, because the image information collected by the camera is essentially similar to the visual information perceived by the human eye, it is widely used to build deep learning models that simulate human visual cognition. Researchers can enable the model to have the ability to detect, track, and predict behavior of multiple types of targets through large-scale annotation and training of images collected by the camera, further promoting the realization of assisted driving and even fully autonomous driving systems.

In terms of system architecture, smart driving vehicles usually adopt a multi-camera collaborative deployment method, installing multiple camera modules at different positions on the vehicle body to form a 360-degree all-round environmental coverage capability, thereby achieving obstacle detection while improving the vehicle's responsiveness to complex environmental changes. For example, "A2D2: Audi Autonomous Driving Dataset" mentions the use of 6 cameras for 360-degree all-round coverage monitoring, and nearly half of the data set is collected by camera sensors and 3D object border annotation [4]. This strategy not only improves the spatial coverage efficiency of image acquisition, but also provides solid data support for multi-sensor data fusion and three-dimensional target reconstruction.

Although camera radar has many advantages in autonomous driving systems, such as rich image information, controllable cost, and flexible deployment, it has also exposed a series of limitations and defects in actual application. The most important of these is that its image quality is highly dependent on ambient lighting conditions. When in extreme weather and lighting environments such as strong light glare, dim night, rain and fog obstruction, or backlight, the images obtained by the camera are prone to overexposure, underexposure, blur or even distortion, thus affecting the accuracy of subsequent image recognition and target detection. In addition, although the camera can obtain rich two-dimensional image semantic information, it lacks the ability to directly measure spatial depth and is difficult to provide high-precision target distance information alone, which makes it have certain limitations when purely performing navigation or obstacle avoidance tasks.

2.2 Millimeter Wave Radar

Millimeter wave radar, as one of the special types of radar, plays a vital role in data collection and simulated driving of autonomous driving systems. Millimeter wave radar, also known as frequency modulated continuous wave (FMCW) radar, is a sensor based on frequency modulated electromagnetic waves that can sense the surrounding environment in three dimensions at a long distance. In intelligent driving systems, linear frequency modulated continuous wave (LFMCW) radar is one of the commonly used millimeter wave radars in smart cars [5]. Compared with other millimeter wave radars, linear frequency modulated continuous wave radar improves its working principle by emitting linear high-frequency electromagnetic waves (60GHz-300GHz) with triangular modulation and continuous, receiving the signal reflected by the target object through the antenna, and calculating the distance, azimuth, elevation, speed of the object and the signal ratio of the point that may be detected internally. In autonomous driving systems, it can be used as one of the leading sensing components in applications such as adaptive cruise control (ACC), autonomous driving, and industrial applications.

Their main advantage is that they can simultaneously measure the distance and radial velocity of moving objects [6]. Figure 1 shows the structure of millimeter wave FMCW radar [7].

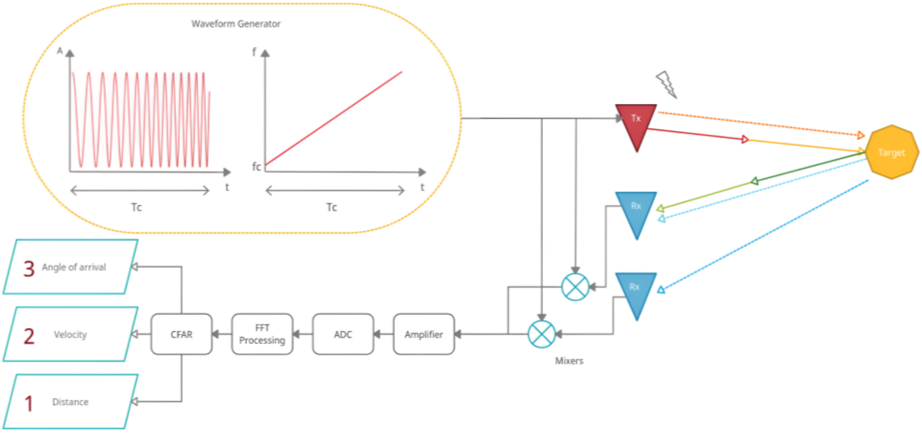


Fig. 1. Structure of millimeter wave FMCW radar

As a common perception sensor in high-precision autonomous driving systems, the main advantage of millimeter-wave radars over other types of sensors such as camera sensors is their efficient computing capabilities. They can calculate the distance and radial velocity of an object in a short time and have real-time monitoring capabilities. At the same time, when driving in harsh environments, millimeter-wave radars have the ability to penetrate fog, smoke, and dust, and have good environmental adaptability to different lighting conditions and weather [8]. At the same time, millimeter-wave radars can measure the position and relative motion state of objects within a long distance (250m), which can provide important driving predictions for high-precision autonomous driving systems and significantly improve the safety of autonomous driving. However, the disadvantages of millimeter-wave radars are also obvious. Since the frequency of the emitted electromagnetic waves cannot be guaranteed to be consistent, the algorithms for receiving and filtering effective wavelengths require relatively high restrictions and accuracy. This situation will also cause millimeter-wave radars to generate false alarms, false touches, and other related problems in autonomous driving systems. Due to real-time measurement, it requires a huge amount of computing resources. In addition, millimeter-wave radars also have the disadvantages of being unable to provide clear object shape, color, or category information, and it is difficult to independently achieve semantic recognition of targets.

Currently, millimeter-wave radar is developing towards miniaturization, integration, high resolution and low power consumption, and its chip design is making it more suitable for mass-produced vehicles. In the future, in L3 and above autonomous driving systems, it will still be one of the core perception modules and play an irreplaceable role in sensor fusion systems.

2.3 LiDAR Sensor

In autonomous driving, LiDAR, as a high-precision active sensor, has very broad application potential. Its working principle is to emit a laser beam at the transmitting end and receive the light wave reflected from the surface of the object or obstacle at the receiving end and then obtain the precise distance between the target object and the sensor by calculating the time of flight (ToF). Based on this mechanism, LiDAR can construct a high-resolution three-dimensional point cloud image (3D Point Cloud) around the vehicle, accurately restore the spatial position and contour structure of objects in the environment and provide three-dimensional and quantitative data support for the path planning, obstacle recognition, and map construction of the autonomous driving system. It is worth mentioning that the ranging calculation of LiDAR follows the following physical formula (1):

$$r = \frac{c}{2n} * t \tag{1}$$

Where r represents the measured distance between the target and the sensor, c is the speed of light in a vacuum, n is the refractive index of the propagation medium (usually n ≈ 1 in air), and t is the time difference (flight time) experienced by the laser from emission to reflection. In reference [9], the author further proposed a calculation model for the echo power Pr received by the lidar in actual operation, which can be expressed by formula (2) to describe the energy loss of the laser signal during propagation and reflection:

$$p_r = E_p \times \left(\frac{c\eta Ar}{2r^2 n^2}\right) \beta \times T_r \tag{2}$$

Here, Ep is the total energy of the emitted pulsed laser, c is the speed of light, η represents the overall efficiency of the system, Ar is the aperture area of the receiving optical system at a distance r, β is the reflectivity of the target surface to the laser (determined by the material and the incident angle), and Tr represents the transmission loss factor of the laser in the propagation medium.

Compared with millimeter-wave radar, LiDAR has significant advantages in detection accuracy and spatial resolution. It can clearly capture detailed information such as road edges, obstacles, building outlines and even road surface undulations. It is often used to build high-precision maps (HD Maps) and perform three-dimensional environmental modeling. During autonomous driving, LiDAR can achieve high-precision recognition and positioning of surrounding static and dynamic targets, thereby providing key data support for auxiliary systems to perform path planning, obstacle avoidance and navigation control. One of the core advantages of LiDAR is its excellent spatial sampling capability and high-density point cloud generation method, which can reconstruct the three-dimensional spatial environment around the vehicle in real time with high temporal and spatial resolution, providing an accurate perception model for the vehicle.

LiDARs in autonomous driving systems usually use a rotating structure to achieve 360-degree laser scanning of the vehicle. In combination with the on-board inertial measurement unit (IMU) and multi-point cloud fusion algorithm, positioning accuracy and environmental modeling capabilities can be further improved. This high-precision, multi-angle, and multi-resolution laser scanning feature makes it particularly outstanding in tasks such as obstacle recognition, dynamic tracking, and boundary detection. At the same time, since the last century, people's exploration and development of LiDARs have had very mature literature records and reference resources, and the development of its computing technology and related manufacturing processes have also been widely used in the design and implementation of autonomous driving systems [10]. This deep technical accumulation not only lays a solid foundation for the application of LiDARs in intelligent driving but also accelerates its rapid migration from high-cost platforms to mass-produced models.

Despite this, LiDAR also has certain limitations. First, its performance is easily affected by bad weather such as rain, snow and fog, and the scattering and attenuation of the laser beam in the air will lead to a decrease in perception. On the other hand, because the human eye is more sensitive to lasers of certain wavelengths, regulatory standards have put forward clear requirements for the use of LiDAR. For example, "An Overview of LiDAR Requirements and Techniques for Autonomous Driving" stipulates that LiDAR must comply with laser safety level standards in indoor and outdoor environments. For products using 1550nm wavelength lasers, the average power output of the emitted light signal must be controlled at around 10 milliwatts to limit potential harm to the human body [11]. These restrictions also affect the output power, detection distance and measurement frequency of LiDAR to a certain extent.

In addition, LiDAR itself does not have the ability to recognize information such as color, texture, and semantics, and it is difficult to independently complete the type recognition and semantic understanding of the target object. Therefore, in practical applications, it is usually necessary to perform joint perception with sensors such as cameras. High cost is also an important factor restricting its widespread deployment. At present, although some manufacturers have launched solid-state LiDAR products based on MEMS or OPA technology to reduce volume and cost, their performance still has certain technical barriers in terms of detection angle, distance and point cloud density, and it is difficult to completely replace high-performance rotating equipment.

Therefore, the high precision and stability of LiDAR in the construction of three-dimensional spatial information provide important support for its wide application in future autonomous driving systems. With the continuous advancement of technology, LiDAR is expected to further achieve low cost and miniaturization while ensuring detection accuracy and robustness, helping the intelligent driving industry to accelerate implementation and large-scale application.

2.4 Ultrasonic Sensor

Ultrasonic sensors are sensors that detect objects at close range based on the principle of sound wave propagation. They are mainly used to detect obstacles and spatial boundaries around the vehicle. The sound waves emitted by this ultrasonic sensor are usually higher than 20kHz and cannot be heard by the human ear. Figure 2 shows how an ultrasonic sensor works [12]. Based on the principle of ultrasonic sensors, in autonomous driving systems, ultrasonic sensors are mainly used for functional modules such as automatic parking assistance (APA), reversing radar (RPA), low-speed collision avoidance warning, and blind spot detection. Usually, ultrasonic sensors have two transducers, each of which is used as a transmitter and a receiver. However, with the development of technology, MaxBotix sensors only use one special transducer to complete the functions of transmitting and receiving signals, and the measurement is very accurate [13].

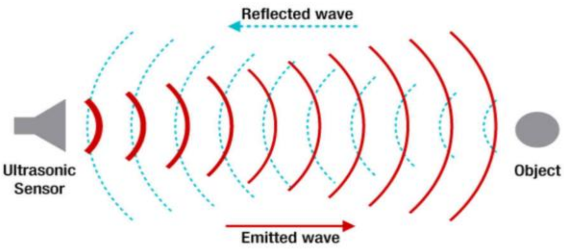


Fig. 2. How an ultrasonic sensor works

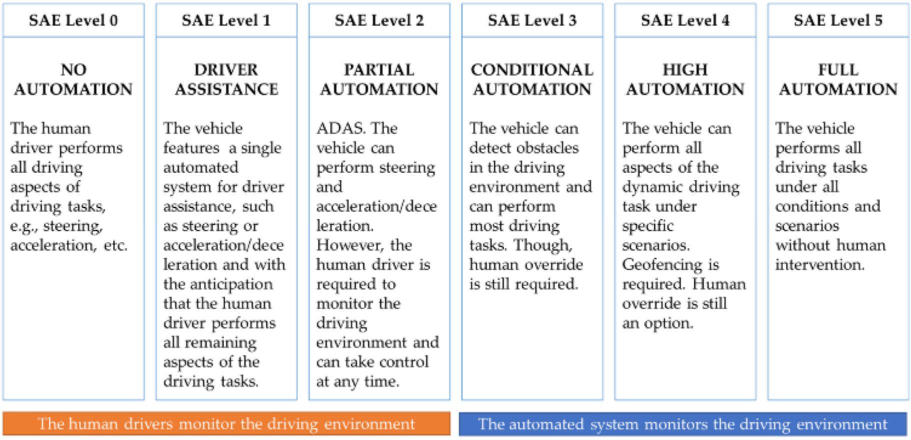
Unlike long-range sensors such as cameras or lidar, ultrasonic sensors have significant advantages in close-range obstacle detection. They can effectively sense low obstacles, walls, car pillars, road edges and other information that is easily missed in vision, and are insensitive to ambient light, and can work stably in low-light environments such as at night, in tunnels or underground garages. In addition, because its ranging does not rely on image features, its performance is relatively stable in rainy and foggy weather, making it an important supplement when the camera's perception ability is insufficient.

However, ultrasonic sensors also have their limitations. First, their sensing distance is limited, and it is usually difficult to detect obstacles over 5 meters, which cannot meet the perception needs of medium and long-distance scenes. Secondly, due to the wavelength of sound waves, their resolution is relatively low, and it is difficult to accurately distinguish multiple objects close to each other or judge the shape of objects. In addition, ultrasonic waves are affected by factors such as temperature, wind speed, and air density during propagation, resulting in a certain degree of ranging error. Its reflection ability on the surface of soft materials (such as cloth and grass) is also poor, and there is a certain detection blind spot.

In multi-sensor fusion systems, ultrasonic sensors are still an indispensable component. By working in conjunction with cameras, millimeter-wave radars and other equipment, ultrasonic sensors can effectively make up for the system's perception blind spots in close-range, high-frequency, and low-speed operation scenarios. In the future, with the popularization of technologies such as automatic parking and low-speed unmanned delivery, ultrasonic sensors are expected to play a greater role in low-speed and high-precision perception systems.

3 Future Prospects and Challenges

As autonomous driving technology continues to evolve towards L4/L5 levels, environmental perception systems will face more complex, dynamic, and open traffic environments, which places higher demands on the sensor system's perception accuracy, real-time performance, and cost control. Here are some major development trends, among which Figure 3 shows the level classification of autonomous driving technology.



SAE Level 0	SAE Level 1	SAE Level 2	SAE Level 3	SAE Level 4	SAE Level 5
NO AUTOMATION	DRIVER ASSISTANCE	PARTIAL AUTOMATION	CONDITIONAL AUTOMATION	HIGH AUTOMATION	FULL AUTOMATION
The human driver performs all driving aspects of driving tasks, e.g., steering, acceleration, etc.	The vehicle features a single automated system for driver assistance, such as steering or acceleration/deceleration and with the anticipation that the human driver performs all remaining aspects of the driving tasks.	ADAS. The vehicle can perform steering and acceleration/deceleration. However, the human driver is required to monitor the driving environment and can take control at any time.	The vehicle can detect obstacles in the driving environment and can perform most driving tasks. Though, human override is still required.	The vehicle can perform all aspects of the dynamic driving task under specific scenarios. Geofencing is required. Human override is still an option.	The vehicle performs all driving tasks under all conditions and scenarios without human intervention.

The human drivers monitor the driving environment

The automated system monitors the driving environment

Fig. 3. Overview of the six different levels of driving automation described in the SAE J3016 standard [14]

3.1 Sensor Fusion

Although there have been many studies on sensor fusion that have made good progress, there are still more fusion methods that can be explored and optimized. At present, sensor fusion has become an indispensable key technology in autonomous driving systems, especially the data fusion of multiple types of sensors such as millimeter wave radar, lidar, camera and ultrasonic sensor, which enables the environmental perception system to obtain more accurate and comprehensive information. However, since each sensor performs differently in different environments, how to effectively integrate data from different sensors, especially to deal with noise, error and information redundancy, is still one of the challenges in current technology.

In recent years, some new research and methods have been proposed, especially sensor fusion technology based on deep learning, which can adaptively learn features from data and achieve more efficient information fusion than traditional algorithms. For example, the multimodal fusion method based on "convolutional neural network (CNN)" eliminates noise and enhances recognition ability by learning the feature representation of different sensors [15]. In addition, the application of graph neural network (GNN) and Transformer structure also provides a new breakthrough direction for improving the accuracy and efficiency of sensor fusion. Through these advanced algorithms, autonomous driving systems can achieve more accurate obstacle detection, path planning and behaviour prediction in complex environments.

3.2 Improvement of Intelligent Perception and Computing Capabilities.

With the rapid development of AI technology, sensors will no longer be just "information collectors". Future sensor systems will have preliminary computing and judgment capabilities and will be able to realize real-time data processing by embedding edge computing frameworks. Some sensors will no longer simply transmit raw data, but will be able to directly perform preliminary analysis and processing of information, greatly reducing dependence on central processing units and improving response speed. In addition, with the improvement of computing power, perception systems will be able to better handle complex tasks in dynamic environments, such as real-time obstacle identification and decision-making under complex roads or severe weather conditions. Transformer-based deep learning models, such as multimodal Transformer models, have begun to be applied in autonomous driving perception systems. These models effectively fuse multimodal data from different sensors through deep learning algorithms, process multidimensional information from sensors such as vision, radar, and lidar, and thus improve the environmental perception and prediction capabilities of autonomous driving systems [16]. Further development of such technologies is expected to make autonomous driving systems more adaptable and accurate when facing complex scenarios.

3.3 Extreme scenario adaptation and stability remain key challenges.

In real complex traffic environments, autonomous driving systems still have to face extreme situations such as rain, fog, snow, darkness, glare, reflection, and occlusion. How to improve the stability and robustness of sensor systems in such environments is an important bottleneck that needs to be overcome in future perception systems. For example, lidar is sensitive to rain and fog, cameras are prone to failure in backlight or at night, and millimeter-wave radars have problems such as false detection. It is necessary to further optimize hardware performance and perception algorithms to improve the system's performance in uncertain environments.

4 Conclusion

This paper systematically reviews the core environmental perception sensors widely used in current autonomous driving systems, including cameras, millimeter-wave radars, lidars, and ultrasonic sensors, and deeply analyzes the advantages and limitations of various sensors in different application scenarios from multiple dimensions such as perception accuracy, working mechanism, environmental adaptability, and deployment cost. Cameras have become one of the main sensors for building semantic understanding due to their low cost, strong image expression capabilities, and friendliness to deep learning models; millimeter-wave radars perform well in bad weather such as rain and fog, and have excellent long-distance speed and distance measurement capabilities; lidars have high spatial resolution and three-dimensional mapping capabilities, which are suitable for high-precision scene perception; ultrasonic sensors show unique value in close-range obstacle detection and automatic parking. Studies have shown that a single sensor often has shortcomings such as insufficient information and poor environmental adaptability when facing complex and changing dynamic traffic environments. Therefore, improving system robustness and accuracy through multi-source heterogeneous sensor fusion has become a key path to achieve high-level autonomous driving.

In addition, with the rapid development of artificial intelligence, edge computing, and multimodal deep learning technologies, perception systems are evolving towards "intelligent front-end", "local computing", and "fast response". The sensors of the future will not only be data collection units, but will also have preliminary processing and decision-making capabilities. In particular, perception fusion models based on structures such as graph neural networks and Transformer are significantly improving the system's recognition, prediction and path planning capabilities in complex environments. While technology continues to iterate, autonomous driving perception systems still face some practical challenges, such as the high cost of high-performance sensors, the stability of perception performance in extreme weather, and the standardization of safety standards. These issues still need to be continuously broken through. In summary, this article not only provides researchers with a systematic review of current mainstream perception technologies but also provides theoretical support and technical references for the subsequent optimization design of autonomous driving systems at the perception level, improvement of fusion strategies, and industrialization.

References

1. Wang, P.: Research on Comparison of LiDAR and Camera in Autonomous Driving, Journal of Physics: Conference Series, 2093(1), 012032, 2021.
2. Geng, K., G. Dong, G. Yin, and J. Hu, Deep dual-modal traffic objects instance segmentation method using camera and lidar data for autonomous driving, Remote Sens., 12(20), 1–22, Oct. 2020.
3. Arikumar, K. S., A. Deepak Kumar, T. R. Gadekallu, and K. Tamilarasi, Real-time 3D object detection and classification in autonomous driving environment using 3D LiDAR and camera sensors, *Electronics*, 11(24), 4203, Dec. 2022.
4. Geyer, J., Kassahun, Y., Mahmudi, M., Ricou, X., Durgesh, R., Chung, A. S., ... & Schuberth, P. A2d2: Audi autonomous driving dataset. arXiv preprint arXiv:2004.06320, 2020.
5. Zhu, B., Y. Sun, J. Zhao, S. Zhang, Zhang and D. Song, Millimeter-Wave Radar in-the-Loop Testing for Intelligent Vehicles, in IEEE Transactions on Intelligent Transportation Systems, 23(8), 11126-11136, Aug. 2022,
6. Abdu, F. J., Zhang, Y., Fu, M., Li, Y., & Deng, Z. Application of Deep Learning on Millimeter-Wave Radar Signals: A Review. Sensors, 21(6), 1951. (2021).
7. Venon, A., Y. Dupuis, Vasseur and Merriaux, Millimeter Wave FMCW RADARs for Perception, Recognition and Localization in Automotive Applications: A Survey, in IEEE Transactions on Intelligent Vehicles, 7(3), 533-555, Sept. 2022,
8. Zhou, T., Yang, M., Jiang, K., Wong, H., & Yang, D. MMW Radar-Based Technologies in Autonomous Driving: A Review. Sensors, 20(24), 7283. (2020).
9. Y. Li and J. Ibanez-Guzman, Lidar for Autonomous Driving: The Principles, Challenges, and Trends for Automotive Lidar and Perception Systems, in IEEE Signal Processing Magazine, 37, 4, 50-61, July 2020,
10. Royo, S., & Ballesta-Garcia, M. An Overview of Lidar Imaging Systems for Autonomous Vehicles. Applied Sciences, 9(19), 4093. (2019).
11. D. Bastos, Monteiro, A. S. R. Oliveira and M. V. Drummond, An Overview of LiDAR Requirements and Techniques for Autonomous Driving, 2021 Telecoms Conference (ConfTELE), Leiria, Portugal, 2021, 1-6,
12. Toa, M., & Whitehead, A.: Ultrasonic sensing basics. Dallas: Texas Instruments, 53-75 (2020).

13. Budisusila, E. N., M. Khosyiin, S. A. D. Prasetyowati, B. Y. Suprapto and Z. Nawawi, Ultrasonic Multi-Sensor Detection Patterns On Autonomous Vehicles Using Data Stream Method, 2021 8th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI), Semarang, Indonesia, 2021, 144-150
14. Yeong, D. J., Velasco-Hernandez, G., Barry, J., & Walsh, J.: Sensor and Sensor Fusion Technology in Autonomous Vehicles: A Review. *Sensors*, *21*(6), 2140 (2021).
15. Xu, Y., Zhang, Z., & Li, X.: Deep Learning-Based Sensor Fusion for Autonomous Driving. IEEE Transactions on Intelligent Transportation Systems, 23(4), 1234-1245(2022).
16. Yang, H., Lee, Y., & Koo, J.: Multi-modal Sensor Fusion for Autonomous Driving: A Transformer-based Approach. Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 2021, 56-61(2021).