The Advances of Perception Technology in Autonomous Driving

Yifan Tang[1*]

[1]School of Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou, China
*Yifan.Tang23@student.xjtlu.edu

Abstract. The advent of autonomous driving technology represents a significant milestone in the evolution of the transport industry. This innovation has profoundly changed the way of travelling and, in certain instances, improved road safety, while at the same time fostering the development and innovation of associated technologies. This review aims to explicate the overarching categorization and present condition of both conventional and currently prevalent perception technologies within autonomous driving, as well as highlight the hurdles faced throughout the transition from conceptualization to practical implementation. In contrast to conventional technologies, the domains of perception technology, including hardware technology and software technology within autonomous driving are undergoing continuous intellectual enhancement and refinement. Notably, perception technology, leveraging technologies such as Computer Vision (CV) and Deep Learning (DL) in conjunction with sensor fusion, enhances data processing efficiency, perpetual learning capacities, and adaptability. Through detailed explication, categorization, and comparison of these technologies, a holistic and intuitive comprehension of the perception technology as an integral part of autonomous driving can be achieved.

Keywords: Autonomous Driving, Perception Technology, Sensor, Computer Vision, Deep Learning

1 Introduction

As automated driving technology garners more focus, its commercialization is progressively manifesting into reality, assuming a crucial role in the realm of transportation [1]. As early as 2016, the U.S. Department of Transportation unveiled the “Federal Automated Vehicles Policy”, marking the forthcoming advent of the era of autonomous vehicles. In 2020, the United States formally issued an updated autonomous vehicle guidance document titled “Ensuring the U.S. Leadership in the Field of Autonomous Driving Technology: Autonomous Vehicle 4.0”, setting forth the federal-level guidelines for the advancement and incorporation of autonomous vehicles [1]. It is precisely due to the introduction of these policies and the advancement of related technologies that autonomous vehicles have streamlined transportation and enhanced the significance of sectors such as healthcare, military, space computing, agriculture, and supply chain management. In each of these fields, self-driving cars

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_28

assist humans in carrying out a diverse range of tasks [2]. Clearly, autonomous driving is increasingly becoming intertwined with daily life.

An example of an autonomous driving platform for a Hyundai IONIQ electric vehicle is illustrated. The implementation of function autonomous driving capabilities is mainly dependent on two cameras and one LiDAR sensor. The system comprises three computers dedicated to perception, planning, and control functions. A high-definition map database is utilized to facilitate the localization of the ego vehicle's position and to formulate driving plans [3]. The Controller Area Network (CAN) serves as an electronic control system, which consists mainly of the steering wheel, accelerator pedal, and brake pedal to manage the operations [4]. This article will concentrate on the perception system.

Autonomous driving technology amalgamates several cutting-edge intelligent machine technologies to offer unparalleled convenience and safety in transportation [5]. Perception technology, as a core part of autonomous driving technology, is the main application area of these technologies. It is primarily comprised of both hardware and software components. The hardware aspect mainly consists of devices such as cameras and radars, while the software component encompasses artificial intelligence technologies, which are developed through the application of computer vision (CV) and deep learning (DL) methodologies. These components help autonomous driving systems acquire critical information regarding the ego vehicle's location, road conditions, and the surrounding traffic environment, which can collectively empower vehicles to navigate and operate with minimal to no human intervention [6]. Perception is a system designed to identify traffic lights and moving objects through the utilization of cameras and LiDAR Sensors [3]. When integrated with complementary technologies like artificial intelligence (AI), these sensors facilitate algorithms in more effectively processing data, perpetually refining the perception and decision-making frameworks of autonomous vehicles. By effectively integrating software and hardware, the vehicle's capability to perceive its surrounding environment, respond to emergencies, and plan optimal paths during the autonomous driving process can be significantly enhanced. This enhancement significantly bolsters the safety and dependability of autonomous driving systems [1].

The objective of this article is to elucidate the current status and specific classification of perception technology within the domain of autonomous driving, while also addressing the existing challenges and limitations. Despite the continuous iterative advancements in hardware associated with perception technology and the maturation of software technologies, there remains a notable deficiency in comprehensive reviews of the latest research within this domain. This paper seeks to address this gap by providing a thorough examination of recent developments in the field.

2 Sensor

Vehicles engineered for autonomous driving must be equipped with the ability to accurately perceive their surroundings and respond effectively to obstacles and other participants in traffic, and hardware technology plays an important role in it. The hardware technology employed in perception systems primarily comprises a variety of sensors and sensor fusion technology. Similar to how a human driver relies on multiple senses to operate a vehicle, autonomous vehicles utilize a diverse array of sensors to perceive their environment [7]. Among these sensors, the primary types are LiDAR Sensors, Radar, Cameras, Motion and Angle Sensors, Ultrasonic Sensors and GPS Sensors. Table 1 shows the model and data of sensors used in autonomous driving.

Table 1. Specifications of Various Sensors Used in Autonomous Vehicles [8]

Sensor Type	Signal type	Working range
LiDAR Sensors	Infrared	Mid and short-range
Ultrasonic Sensors	Ultrasound	Proximity
GPS Sensors	Microwave	Global
Cameras	Visible Light	Long, mid, and short-range
Radar	Microwave	Long and short-range

The specific functions of the most commonly used sensors are as follows.

Motion and Angle Sensors: It is primarily employed to measure acceleration along the longitudinal and vertical axes, monitor wheel speed, and ascertain the position of the front wheels. It plays a crucial role in transmitting this essential information to the drive system and enables adjustments to the vehicle's body position [8].

LiDAR Sensors: It operates by transmitting and receiving laser signals to acquire point cloud data (PCD) with exceptional spatial resolution on the order of centimeters and provides comprehensive three-dimensional spatial information [9]. The sensor utilizes this information to accurately determine the distance to the object [8].

Cameras: It provides clear forward distance measurement and 3D mapping of the surrounding environment [10]. This approach allows for a more accurate determination of the distance between the vehicle and surrounding objects, thereby enhancing driving safety.

Although the variety of sensors is extensive, sensor fusion technology can effectively integrate these different sensors. Sensor fusion is defined as the process of integrating data from multiple sensors to yield results that surpass those obtained from individual sensors. As a vital component in the realm of autonomous vehicles (AV), sensor fusion capitalizes on the advantages of diverse sensors to improve the perception of the surrounding environment [8]. Each sensor has its limitations to varying degrees. Sensor fusion addresses these information deficiencies by optimally combining data from multiple sensors, thereby leveraging their respective advantages. This approach enhances redundancy and reliability in the perception system [7][8]. The most widely used sensor fusion method currently involves the integration of cameras and LiDAR Sensors [11]. By integrating the advantages of cameras and LiDAR Sensors, sensor fusion technology enhances the environmental perception of autonomous driving and delivers more precise data for subsequent path planning, thereby improving both driving efficiency and safety. Cameras capture high-resolution images that are ideal for recognizing the appearance and texture characteristics of objects, whereas LiDAR Sensors offers accurate information regarding the location, distance, and shape of those objects [11]. The detection results from LiDAR Sensors are typically represented as images formed by point cloud data collected through scanning [12]. A denser point cloud correlates with a higher accuracy of the sensor. The point cloud view refers to the projection of a three-dimensional point cloud onto a two-dimensional representation to align with image features; however, this process inevitably results in some loss of information [11]. The effectiveness of the camera's perception is primarily demonstrated through the pixel resolution of the two-dimensional image it produces; higher pixel counts result in clearer and more detailed images. After processing, additional feature images can also be generated. Figure 1 is an example of an image captured by the camera.

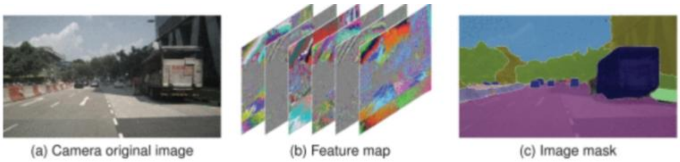

Fig. 1. Image captured by camera [11]

The perception results from the two sensors for the same scene are integrated, whereby the LiDAR point cloud and the 2D images are extracted independently, and the outcomes are analyzed for 3D object detection [11]. The results are illustrated in Figure 2.

Fig. 2. The results of sensor fusion technology [11]

By comparing the images, it is evident that the results produced using sensor fusion technology are more accurate than those obtained from the two sensors used independently. This demonstrates that sensor fusion technology enhances the perception capabilities of autonomous driving and compensates for the limitations inherent in individual sensors.

3 Computer Vision Technology (CV)

As a component of autonomous driving perception technology, software technology also plays a crucial role in perceiving the environment, processing data collected by sensors and relaying the final perception results to the subsequent decision-making stage. Given the stringent safety requirements for operating autonomous vehicles, this software must handle inputs in real-time while sensing the environment—such as those from hardware technologies like cameras—in real-time, ensuring quick and accurate processing to maintain stable and safe driving conditions [13]. CV is one of the most widely used image recognition technologies in autonomous driving. It is capable of capturing and analyzing image and video data from the road environment, thereby enabling vehicles to perceive and comprehend their surroundings effectively [5]. In the subsequent section, OpenCV will be presented as a case study to elucidate its processes and the relevant algorithms. The CV technique is comprised of three primary components: preliminary processing and feature extraction. The objective of this methodology is to obtain the most lucid and efficacious image, which can subsequently be utilized in path planning, prediction, and the tracking of surrounding objects [14].

Once the camera and other sensors acquire information about the surrounding environment, OpenCV will process this data primarily to filter out irrelevant areas within the video stream [15]. For instance, video streams frequently contain significant amounts of noise, and CV employs Gaussian filtering techniques to mitigate the effects of this noise interference [16]. Its relevant formula is as follows.

The Gaussian scale space of an image can be generated by applying a series of Gaussian convolutions at varying scales, as demonstrated in the following equation [5].

$$L\ (x, y, \delta) = G\ (x, y, \delta) * I\ (x, y, \delta)$$

$G\ (x, y, \delta)$ denotes a Gaussian kernel function, i.e.,

$$G\ (x, y, \delta) = \frac{1}{2\pi\delta^2} e^{\frac{x^2+y^2}{2\delta^2}}$$

where δ denotes the scale space parameter, which is derived from the standard deviation of the Gaussian normal distribution function. As the value of δ increases, the processed image becomes increasingly blurred, resulting in a larger scale representation [5].

Following the initial processing stage, the CV technology is advanced to the feature extraction stage. At this point, some algorithms like the Canny and Sobel algorithm are mainly applied to extract the primary features of the image, thus facilitating subsequent analysis and processing. For example, if using Sobel algorithm, the following equation will be helpful.

$$\theta = \arctan\left(\frac{I_y}{I_x}\right), A = arctan\sqrt{I_y^2 + I_x^2}$$

It is evident that, by following these steps, OpenCV is capable of displaying real-time feedback images at a rate of 20 frames per second. The utilization of CV in a variety of image processing applications is largely attributable to these fundamental steps.

4 Deep Learning Technology (DL)

Recently, autonomous driving has emerged as a prominent area of research, with image recognition technology identified as one of the critical components enabling autonomous vehicles to navigate safely on the road [17]. As previously mentioned, sensor fusion and CV techniques can be used for image processing. However, given the complexity of the road situation, the simple use of these techniques to process images is insufficient. Consequently, the DL technique is often applied during image processing to enhance the depth of the image processing. Deep learning (DL) can be defined as a specialized subset of machine learning that draws inspiration from the architecture and functionality of neural networks [18]. This characteristic enables DL to autonomously learn and extract valuable feature information from extensive image datasets, thereby facilitating precise recognition and classification of targets [5].

In the domain of autonomous driving perception technology, DL has become a pervasive component. For instance, it is employed for the advanced processing of images acquired through sensor fusion technology, as well as for the post-processing of images in CV applications. This enhances the recognizability of the images and assists vehicles in swiftly and accurately adapting to a variety of complex driving scenarios [19]. The present paper will utilize the example of DL in the processing of point cloud images within the context of sensor fusion technology to illustrate the processes and significance of deep learning in autonomous driving technology.

The development of Deep Learning (DL) has enabled the analysis of complex patterns and representations within data, thereby enhancing the flexibility and robustness of LiDAR point cloud analysis [20]. It has been demonstrated that DL models possess the ability to learn from large datasets, enabling the accurate recognition of LiDAR point clouds and the efficient generalization of new data [21]. It is generally acknowledged that there are two distinct methodologies for employing DL in the context of point cloud map processing, namely Projection-based models and Point-based models.

In the initial approach, the point cloud is projected onto a two-dimensional image, which is then entered into a traditional two-dimensional convolutional neural network (CNN). The CNN extracts features from this image, which are then employed to make predictions related to the specific task at hand (Figure 3) [20].

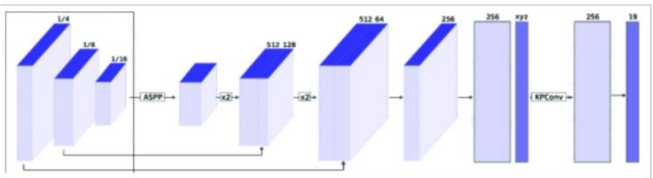

Fig. 3. Projection-based models [20]

The second method operates directly on the point cloud, normalizing the data to extract features, which are then utilized to make predictions related to the specific task at hand [20].

In this process, PointNet or PointNet++ is typically employed as the model of DL, and through the processing of DL, the image is rendered more distinctive, thereby enhancing the perception ability and ensuring driving safety.

5 Limitations & Future outlooks

Despite the continuous advancements in perception technologies for autonomous driving, including improvements in sensors, as well as breakthroughs in Computer Vision (CV) and Deep Learning (DL) technology, the widespread adoption of self-driving vehicles remains a distant prospect for contemporary society [22]. Firstly, in inclement weather conditions, such as heavy rain, snow and dust storms, the sensor's capacity to accurately assess the situation is significantly compromised. This results in a substantial decline in the safety factor. This is primarily attributable to the fact that the sensor is unable to identify or misidentify road signs, lane lines and surrounding objects due to weather conditions [23]. Secondly, the incorporation of a multitude of advanced technologies into autonomous vehicles has led to the emergence of sophisticated sensing systems, which have resulted in substantial financial investments. While the adoption of mass production methodologies has the potential to reduce these costs, the prevailing challenge remains the assurance of safety while concurrently achieving cost-effectiveness and widespread accessibility [22].

While cognizant of the present challenges and limitations of self-driving vehicles, the public also perceives a favorable future for the technology. Despite the fact that the probability of safety incidents associated with autonomous driving technology remains higher than anticipated, this probability is decreasing each year as the technology advances. It is evident that, in view of this trend, the integration of self-driving technology into everyday life is becoming increasingly inevitable. Once pervasive, it is anticipated that the deployment of self-driving technology will engender a substantial enhancement in the quality of people's daily commutes. For instance, the reduction in commuting times could result in a more comfortable and efficient travel experience for passengers [24].

6 Conclusion

The present paper focuses on the classification and description of sensing technologies for autonomous driving. The current perception technologies are divided into two categories: hardware and software. The former mainly includes various types of sensors and sensor fusion technologies, while the latter consists primarily of CV and DL. The paper then analyses the functions and processes of these technologies. In addition, it describes the limitations and future development of sensing technology. This paper addresses a significant gap in the current review of automated driving sensing technologies by synthesizing the main technologies and contributing to the advancement of related research. It is anticipated that in the future, the development of more cost-effective and robust perception technologies will be a major focus.

References

1. Zhu, R., et al.: 'Research on Safety Analysis and Response Methods of Autonomous Driving Technology Based on Artificial Intelligence'. Proc. IEEE Int. Conf. Image Processing and Computer Applications (ICIPCA), Changchun, China, 2023, pp. 1489–1492.
2. Jain, S., et al.: 'Blockchain and Autonomous Vehicles: Recent Advances and Future Directions'. IEEE Access, vol. 9, pp. 130264–130328, 2021.
3. Min, K., Han, S., Lee, D., et al.: 'SAE Level 3 Autonomous Driving Technology of the ETRI'. Proc. 2019 Int. Conf. Information and Communication Technology Convergence (ICTC), Jeju, Korea (South), 2019, pp. 464–466.
4. Sung, K., Min, K., Choi, J.: 'Driving information logger with in-vehicle communication for autonomous vehicle research'. Proc. 2018 20th Int. Conf. Advanced Communication Technology (ICACT), Chuncheon, Korea (South), 2018, pp. 300–302.
5. Wang, Y., Bi, X.: 'The Application of Computer Vision Target Recognition Technology in Autonomous Driving'. Proc. 2024 3rd Int. Conf. Artificial Intelligence and Autonomous Robot Systems (AIARS), Bristol, United Kingdom, 2024, pp. 519–524.
6. Zha, Y., Shangguan, W., Chai, L., et al.: 'Hierarchical Perception Enhancement for Different Levels of Autonomous Driving: A Review'. IEEE Sensors Journal, vol. 24, no. 11, pp. 17366–17386, 1 June 2024.
7. Kovács, L., et al.: 'Sensor design and integration into small sized autonomous vehicle'. Proc. 2022 IEEE 2nd Conf. Information Technology and Data Science (CITDS), Debrecen, Hungary, 2022, pp. 171–176.
8. Jain, S., et al.: 'Blockchain and Autonomous Vehicles: Recent Advances and Future Directions'. IEEE Access, vol. 9, pp. 130264–130328, 2021.
9. Lee, D.-J., Im, J., Won, J.-H.: 'Virtual Lidar Sensor Intensity Data Modeling for Autonomous Driving Simulators'. IEEE Access, vol. 11, pp. 120694–120706, 2023.
10. Shibasaki, N., Taguchi, A., Bao, Y.: 'Depth Estimation using Omnidirectional Stereo Imaging and Machine Learning'. Proc. 2024 Int. Conf. Advanced Mechatronic Systems (ICAMechS), Kusatsu, Shiga, Japan, 2024, pp. 159–164.
11. Wang, X., Li, K., Chehri, A.: 'Multi-Sensor Fusion Technology for 3D Object Detection in Autonomous Driving: A Review'. IEEE Transactions on Intelligent Transportation Systems, vol. 25, no. 2, pp. 1148–1165, Feb. 2024.
12. Yu, J., Yu, C., Lin, C., et al.: 'Improved Iterative Closest Point (ICP) Point Cloud Registration Algorithm based on Matching Point Pair Quadratic Filtering'. Proc. 2021 Int. Conf. Computer, Internet of Things and Control Engineering (CITCE), Guangzhou, China, 2021, pp. 1–5.
13. Jöckel, L., Kläs, M., Martínez-Fernández, S.: 'Safe Traffic Sign Recognition through Data Augmentation for Autonomous Vehicles Software'. Proc. 2019 IEEE 19th Int. Conf. Software Quality, Reliability and Security Companion (QRS-C), Sofia, Bulgaria, 2019, pp. 540–541.
14. Li, J., Zhan, W., Hu, Y., Tomizuka, M.: 'Generic Tracking and Probabilistic Prediction Framework and Its Application in Autonomous Driving'. IEEE Transactions on Intelligent Transportation Systems, vol. 21, no. 9, pp. 3634–3649, Sept. 2020.
15. He, Z.: 'Practical research on lane recognition and driving state monitoring method based on computer vision'. Proc. 2023 IEEE 3rd Int. Conf. Power, Electronics and Computer Applications (ICPECA), Shenyang, China, 2023, pp. 1270–1274.
16. Song, H.: 'The Application of Computer Vision in Responding to the Emergencies of Autonomous Driving'. Proc. 2020 Int. Conf. Computer Vision, Image and Deep Learning (CVIDL), Chongqing, China, 2020, pp. 1–5.

17. Liu, J.: 'Survey of the Image Recognition Based on Deep Learning Network for Autonomous Driving Car'. Proc. 2020 5th Int. Conf. Information Science, Computer Technology and Transportation (ISCTT), Shenyang, China, 2020, pp. 1–6.
18. Khanum, A., Lee, C.-Y., Yang, C.-S.: 'Involvement of Deep Learning for Vision Sensor-Based Autonomous Driving Control: A Review'. IEEE Sensors Journal, vol. 23, no. 14, pp. 15321–15341, 15 July 2023.
19. Jin, H., Jin, Z., Kim, Y.-G.: 'Design of a Deep Learning-Based Autonomous Vehicle Environmental Perception and Decision-Making System'. Proc. 2024 5th Int. Conf. Electronics and Sustainable Communication Systems (ICESC), Coimbatore, India, 2024, pp. 1708–1713.
20. Chowdhary, S. V., Neelima, N.: 'LiDAR Point Clouds in Autonomous Driving Integrated with Deep Learning: A Tech Prospect'. Proc. 2024 Fourth Int. Conf. Advances in Electrical, Computing, Communication and Sustainable Technologies (ICAECT), Bhilai, India, 2024, pp. 1–5.
21. Ramesh, G. B., Chamas, M., Wang, A., et al.: 'An Approach Towards Generalization of Automotive Camera Sensor Data using Deep Learning'. Proc. 2024 Int. Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA), Istanbul, Turkiye, 2024, pp. 1–10.
22. Bocca, A., Baek, D.: 'Automated Driving Systems: Key Advantages, Limitations and Risks'. Proc. 2019 AEIT Int. Conf. Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Turin, Italy, 2019, pp. 1–6.
23. Chougule, A., Chamola, V., Sam, A., et al.: 'A Comprehensive Review on Limitations of Autonomous Driving and Its Impact on Accidents and Collisions'. IEEE Open Journal of Vehicular Technology, vol. 5, pp. 142–161, 2024.
24. Bimbraw, K.: 'Autonomous cars: Past, present and future a review of the developments in the last century, the present scenario and the expected future of autonomous vehicle technology'. Proc. 2015 12th Int. Conf. Informatics in Control, Automation and Robotics (ICINCO), Colmar, France, 2015.