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Review

Autonomous driving system: A comprehensive survey

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Abstract

Automation is increasingly at the forefront of transportation research, with the potential to bring fully autonomous vehicles to our roads in the coming years. This comprehensive survey provides a holistic look at the essential components and cutting-edge technologies that are driving the development and implementation of autonomous driving. It starts by evaluating two critical system architectures that are fundamental to the operation of autonomous vehicles: the layered and end-to-end structures. It then examines the critical areas of scene perception and localization, emphasizing the importance of sensor technologies. These technologies are vital for tasks such as object detection and semantic segmentation, which allow vehicles to understand and navigate their environment. A special focus is given to the complex topic of object detection, along with suggestions for how it can be enhanced. The survey then proceeds to provide detailed discussions on path planning, trajectory prediction, and decision-making processes. These elements are crucial for the smooth navigation of autonomous vehicles, and the survey highlights the role of artificial intelligence (AI) and machine learning in these processes. Overall, the survey presents the rapid progress in the field of autonomous driving, offering a comprehensive assessment of the technologies and innovations that are essential for moving toward a safe and efficient autonomous future.

Introduction

Over the past decade, self-driving/driverless cars have gained increasing popularity worldwide, promoting the autonomous driving revolution (Baruch, 2016). The use of autonomous driving technology can improve mobility in crowded cities, reduce traffic congestion, and improve travel safety (Nunes & Axhausen, 2021). The British Road Research Laboratory showed a video of autonomous driving, in the early 1970s, which aroused huge interest in both academia and industry. Since then, huge efforts have been devoted worldwide by researchers and engineers from around the world to improve the autonomous technology. In 1984, the U.S. Defense Advanced Research Projects

Agency (DARPA) partnered with the army to launch the Autonomous Land Vehicle (ALV) program. Since the 1980s, many famous universities such as Carnegie Mellon University (CMU), Stanford University, and Massachusetts Institute of Technology (MIT) etc., have successively joined the research on autonomous driving. Good examples include the NavLab series of intelligent vehicles developed by Carnegie Mellon University in the United States (Thorpe et al., 1988) and the ARGO test vehicle developed by the VisLab Laboratory of the University of Parma in Italy (Bertozzi et al., 2006). In addition to active research in the field of unmanned driving underpinned by scientific and research institutions, many automobile manufacturers such as Audi, BMW, Ford, General Motors, Mercedes, Tesla, Volvo and so on also began to deploy in the field of unmanned vehicles since the start of the decade of the 2010s (Greenblatt, 2016). Some companies even adopt the "one-stop" SAE Level 4+development route for designing commercial autonomous driving. Since the DARPA Grand Challenge in 2004 and 2005, data-driven, machine learning-based techniques have been widely used in autonomous driving and is translating into a world of computer-controlled vehicles with autonomy and intelligence.

In order to eliminate the inconsistency and confusion in the terminology used in the autonomous industry, Society of Automobile Engineers (SAE) proposed to define an accurate and consistent vocabulary, launched as an official document named SAE-J3016 in 2014, which clearly classified Levels of Driving Automation on a scale of 0 to 5 (International, 2023), as shown in Fig. 1. The higher the level, the higher the degree of automation. However, the current autonomous driving is still not a fully stable technology per se, and has been at the level 2 for years. The jump from Level 2 to Level 3 require craftsmanship, complex formulations and elaborate implementations, which presents severe challenges and introduces excessive cost and uncertainty to the autonomous process. Safety and robust security operation remain major factors in the market for the foreseeable future. Careful consideration should be given to how to transform autonomous driving from niche to widespread commercial viability. Moreover, the accuracy and sensitivity of hardware seriously affect the safety of autonomous driving during the daily operation. Various high-cost sensors are difficult to put into use on a large scale. Deep learning has brought about a paradigm shift in the field of AI, empowering computational models with the ability to learn intricate data representations through multiple layers of processing (LeCun et al., 2015). These state-of-the-art methods have made significant advancements across various domains, such as enhancing speech recognition accuracy, achieving remarkable success in visual object recognition tasks, enabling precise object detection, and impacting numerous other areas of research and application. The remarkable achievements of deep learning algorithms have propelled the boundaries of what was previously thought possible in the realm of AI. Deep learning methods offer opportunity to perceive, make predictions about future scenarios, and take decisions that are rational/optimal given these predictions (Ghahramani, 2015). In the realm of autonomous driving, machine learning and deep learning have permeated various domains (Bachute & Subhedar, 2021). However, the black-box and inexplicable nature of neural networks have a huge impact on the perception, decision, and execution, which makes autonomous driving vulnerable to environmental influences and external interference (Van Brummelen et al., 2018). The current decision planning is mainly based on the planner and lattice state algorithms using vehicle and road models. Therefore, we must carefully consider the security and robustness of deep learning, which has been an unsolved problem for several years. In cloud services, unstable vehicle-to-vehicle (V2V) links and centralized resource allocation methods with high signaling overhead become bottlenecks for safety–critical applications. This can be described as an NP-hard problem that is expected to be solved by specialized network architectures (Tkatek et al., 2020).

Section snippets

Scope of the survey

To extract insights into the structure and patterns embedded within the scientific literature pertaining to autonomous driving, bibliometric networks are constructed (Fig. 2), through the application of VOSviewer (VOSviewer, 2023). The visualization and subsequent analysis of co-occurrence networks, comprised of significant terms, allow for the identification of influential works, notable initiatives, and emergent research directions in the domain. The blueprint not only facilitates a holistic …

System architectures for autonomous driving

The architectural framework underpinning the functionality of autonomous driving systems plays an indispensable role in fortifying their robustness and prognosticating their capacity for prospective expansion (Fig. 3). Herein, we provide an overview of the system architecture essential for autonomous driving. This includes the layered and end-to-end architectures, with the goal of giving readers a foundational understanding of the architectural principles that operate at the systemic level in …

Scene perception and localization

Machine learning play a pivotal role, providing a powerful tool to simplify the complexities of environmental perception and spatial referencing in autonomous driving. This, in turn, promotes a paradigm deeply rooted in data analysis and algorithmic functionalities. This part of the text explores the application of machine learning, with a particular focus on its ability to address challenges related to hardware deployments, especially sensors. Sensors are crucial for tasks such as object …

Motion planning and decision-making

Deep learning has profoundly reshaped the field of autonomous driving, particularly in the facets of motion planning and decision-making, thereby drastically boosting both the performance and safety standards of such vehicles. Motion planning is the process of devising an optimal route from a starting point to a destination, while skirting around obstacles and abiding by a set of constraints. Conversely, decision-making and behavior arbitration involve the intelligent processing of decisions, …

Simulator & scenario generation

Given that deep learning involves a process of trial and error along with data sampling, it is typically essential to initially assess algorithms within a simulated environment before evaluating their performance in a real-world setting (Fig. 11). Hence, the creation of a simulation environment is indispensable for training models, especially in reinforcement learning (Kiran et al., 2021). State-action pairs used for learning can be acquired through the interaction of autonomous driving systems …

Current challenges and limitations

Autonomous mobility is not just about innovating sophisticated systems; it requires the seamless integration of complex subsystems. While both academia and industry are working diligently, the success of autonomous driving systems remains deeply intertwined with the performance of its individual subsystems. This interdependence introduces certain challenges and limitations (Fig. 13):

(1) **Higher Safety Standards**: While autonomous driving systems leverage cutting-edge technology to improve safety, …

…

Outlook and future directions

To truly advance autonomous driving, we need to encourage research partnerships between various industries and academic institutions. The main goal is to make these systems safer and more reliable, ultimately changing how we view and experience travel. Some critical areas to focus on are:

(i) **Tech Innovation Growth**: The horizon of autonomous driving is linked to the pace of technological innovation. Progress in sensor technology, artificial intelligence, processing capabilities, and network …

…

Conclusions

The evolution of autonomous driving technology signifies a transformative juncture in transportation history and societal norms. This survey methodically examines the foundations of autonomous driving, covering system design methodologies, environmental perception, localization, path planning and decision-making. In terms of environmental perception, we underscore the pivotal role of sensors—such as cameras, Lidar, and radar—in object detection and semantic segmentation. The survey also …

Competing interests

The authors declare no competing interests. …

CRediT authorship contribution statement

Jingyuan Zhao: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition, Supervision. **Wenyi Zhao:** Methodology, Formal analysis, Investigation, Writing – original draft. **Bo Deng:** Methodology, Formal analysis, Investigation. **Zhenghong Wang:** Formal analysis, Investigation, Visualization. **Feng Zhang:** Methodology, Investigation. **Wenxiang Zheng:** Methodology, Investigation. **Wanke Cao:** Project …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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...In scenarios involving unknown and dynamically changing environments, whether evaluating performance metrics for similar problems or addressing more complex path planning challenges, learning-based approaches show significant superiority [5,8–11]. In recent years, researchers have summarized the latest advancements in path planning and DRL, including the current state of research in path planning [1,12], the current state of research on the engineering applications of DRL [13–16], and its breakthrough applications in autonomous driving [4,17–19]. Additionally, there have been comprehensive reviews focusing on the broader aspects of DRL and optimization problems [20]....

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...Similarly, object detection technology is also important in modern society. For example, object detection technology has made autonomous driving [11–16] possible, allowing cars to autonomously recognize objects on complex roads and safely avoid obstacles while traveling on the road. Object detection technology also has deep attainments in the medical [17–21] field, which can help doctors initially screen lesion images and improve the efficiency and accuracy of their diagnosis....

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