Autonomous Driving for a 1:4 Scaled Vehicle

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***Abstract*—Autonomous vehicles rely on a combination of multiple modules to achieve fully autonomous navigation, including localization, control, navigation/planning, and an overarching system architecture. This paper reviews recent advancements (2020-present) in each of these modules, focusing on techniques that improve the accuracy, efficiency, and robustness of autonomous driving systems. The literature analyzed includes studies on sensor fusion for localization, advanced control strategies for lane-keeping and lane-changing, path planning and obstacle avoidance algorithms, and comprehensive architectures integrating these components.**

I. Introduction

Autonomous driving has become one of the most researched topics in intelligent transportation systems, with significant progress in perception, decision-making, and control. The development of a reliable self-driving system depends on multiple key modules: localization, control, navigation/planning, and system architecture. The localization module ensures that the vehicle can determine its position accurately using sensor fusion techniques. The control module is responsible for maintaining vehicle stability through speed and steering adjustments. The navigation/planning module enables path planning and obstacle avoidance in dynamic environments. Finally, an overarching system architecture is required to integrate these modules effectively.

This literature review provides an in-depth analysis of state-of-the-art methods in each of these areas, with a focus on research published from 2020 onward. The review examines advancements in deep learning-based sensor fusion for localization, model predictive control strategies for lane keeping and lane changing, reinforcement learning approaches for navigation, and modular architectures for integrating all autonomy modules.

II. Literature Review

A. Localization Module

The localization module is essential in autonomous vehicles as it allows the vehicle to learn where it lies in the environment and if a map is available, the vehicle can determine its position within the map and if there is no map available, techniques such as Simultaneous Localization and Mapping (SLAM) allow the vehicle to accurately create a map of the environment in real-time. This allows the vehicle to navigate precisely and avoid obstacles in its path. The localization relies on the use of sensors which can be categorized into proprioceptive sensors which measure the internal state of the vehicle, such as encoders and gyropscopes and exteroceptive sensors which observe the external environment such as LiDAR and cameras. However, the sensor measurements are often not accurate as they are affected by noise and environmental conditions. This issue can be improved by the use of multiple sensors at the same time to improve the accuracy of localization. This process is called sensor fusion which is combining the data readings from different sensors to eliminate faulty readings and improving accuracy. In the literature, there were several approaches carried out to enhance localization of the vehicle. In [1], the authors focused on the use of deep learning techniques for sensor fusion in autonomous vehicles perception, localization and mapping. Their work showed that the use of convolutional neural networks (CNNs) and recurrent neural networks (RNNs), improve feature extraction from multiple sensor modalities. The CNNs are mostly better for perception and RNNs are better for localization. They explored three levels of sensor fusion which are:

1) Early Fusion: The raw data from the sensors is merged before any processing occurs leveraging deep learning models to extract and align features.
2) Mid-Level Fusion: Features of each sensor are extracted separately then they are combined together in a shared representation space
3) Late Fusion: Each sensor data is processed and evaluated on its own and later merged together before making the decision

Their results showed that deep learning models outperform traditional probabilistic approaches such as the Kalman Filter however, they require very high computation power. In [2], the authors compared different state-of-the-art localization techniques and analyzed their overall performance in autonomous vehicles applications. They proposed a Localization Algorithm Operations Capability (LAOC)-based equivalent comparison method to evaluate the computational complexity of different localization techniques. Their results showed that LiDAR-Based Localization showed high performance and accuracy but require very-high computation capability in real-time. Vision-Based localization can achieve high precision of the vehicle position but may require high GPU acceleration to process huge image data and may fail in case of bad lighting or bad weather. Vehicle-to-everything(V2X) offer a good cost-efficient localization technique but require a good signal and network coverage. Finally, data-fusion based techniques are needed to balance the cost, accuracy and efficiency.

B. Control Module

The control module in autonomous vehicles is responsible for maintaining stability, ensuring smooth lane keeping, and enabling safe lane changes. This requires precise longitudinal control (speed regulation) and lateral control (steering for lane following and changing). Recent studies have explored various control strategies to enhance these functionalities.

Longitudinal and lateral control are critical aspects of autonomous driving. A study by [3] proposed a model that effectively tracks both longitudinal and lateral trajectories to achieve smooth lane changes. The approach integrates real-time trajectory generation and vehicle dynamic control to ensure stability, even under high-speed conditions up to 120 km/h. The researchers validated their model using simulation environments, demonstrating improved vehicle trajectory tracking and minimized lateral deviations during lane-changing maneuvers.

Beyond traditional control models, advancements in decision-making algorithms have significantly improved autonomous vehicle performance. Research by [4] explores different methodologies, including rule-based controllers, machine learning, deep learning, and probabilistic approaches. These methods enhance the vehicle's ability to respond to dynamic driving environments, allowing for adaptive speed control in lane keeping and precise lateral motion adjustments in lane changes. The study highlights the integration of model predictive control (MPC) with reinforcement learning-based techniques, enabling real-time adjustments to traffic flow variations and obstacles.

Furthermore, an optimal H_∞ control method has been introduced to enhance lateral dynamics in autonomous vehicles. The study by [5] presents a robust control strategy aimed at minimizing position and orientation tracking errors while ensuring vehicle stability. This model incorporates real-time lane detection and video-processing algorithms, allowing the autonomous system to maintain accurate lane tracking under different road conditions. The simulation results demonstrate a significant reduction in lateral deviations and enhanced trajectory stability, making it a promising approach for real-world implementation.

These studies collectively contribute to the development of robust control strategies for autonomous vehicles, improving their ability to navigate complex driving environments safely. By integrating trajectory optimization, adaptive decision-making, and advanced control algorithms, modern control systems are achieving higher reliability and efficiency in autonomous vehicle operations.

C. Navigation/Planning Module

The navigation and planning module is crucial for autonomous vehicles, enabling them to determine optimal paths and avoid obstacles in dynamic environments. Recent advancements have introduced various methodologies to enhance path planning and obstacle avoidance capabilities.

One notable approach involves the integration of attention mechanisms within end-to-end architectures. [6] explored this by incorporating multimodal inputs, such as images and LiDAR data, into an attention mechanism module. This system automatically learns and prioritizes significant environmental features, allowing the vehicle to focus on critical information during navigation. The study demonstrated that this method effectively improves obstacle avoidance and path planning, leading to safer and more efficient autonomous driving.

Another significant development is the application of deep reinforcement learning (DRL) for emergency obstacle avoidance. [7] proposed a DRL-based planning strategy that considers both safety and passenger comfort. By training the system in various traffic scenarios, the autonomous vehicle learns to make real-time decisions that balance collision avoidance with smooth maneuvering. Simulation results indicated that this approach enhances the vehicle's ability to navigate complex environments while maintaining a comfortable ride for passengers.

Additionally, the use of potential field methods has been revisited to address occlusion challenges in path planning. [8] introduced an occlusion-aware path planning strategy that leverages a potential field method combined with responsibility-sensitive safety principles. This approach enables the vehicle to account for partially or fully occluded obstacles, generating smoother paths and reducing the likelihood of sudden evasive maneuvers. The proposed method was validated through simulations, showing improved performance in scenarios with visual obstructions.

These studies collectively advance the navigation and planning capabilities of autonomous vehicles, offering diverse strategies to tackle the complexities of real-world driving environments.

D. Autonomous Vehicle Architecture Integrating All Modules

The development of a cohesive and efficient architecture is paramount for the seamless integration of various modules in autonomous vehicles, including perception, localization, planning, and control. Recent research has introduced several innovative approaches to address this integration challenge.

[9] proposed a hybrid software architecture that combines modular perception and control modules with data-driven path planning. This architecture was evaluated during the 2023 CARLA Autonomous Driving Challenge, achieving top positions in multiple tracks. The hybrid approach allows for flexibility and robustness in dynamic urban environments, effectively integrating traditional modular pipelines with end-to-end learning techniques.

[10] presented an adaptable automated driving stack designed for scalability and ease of integration. The modular design facilitates the rapid incorporation and testing of new research approaches across different vehicle platforms, including shuttles and passenger cars. This stack encompasses all essential components, such as localization, perception, planning, control, and safety modules, and has been validated in real-world traffic scenarios.

[11] detailed the design of a prototypical platform for autonomous and connected vehicles, emphasizing both mechanical aspects and software components. The architecture integrates modules for ego-localization, environment perception, motion planning, and actuation. Experimental tests in urban-like environments demonstrated the platform's effectiveness in real-world applications.

These studies collectively advance the field of autonomous vehicle architecture by offering diverse strategies for integrating essential modules, thereby enhancing the overall functionality and reliability of self-driving systems.

III. Conclusion

Autonomous vehicle development relies on the seamless integration of localization, control, navigation, and system architecture. Sensor fusion techniques enhance localization accuracy, while advanced control strategies such as MPC and reinforcement learning improve vehicle stability. Navigation methods, including deep learning and potential field approaches, optimize path planning and obstacle avoidance. Hybrid architectures integrating modular and end-to-end learning approaches enable efficient system design. Future research should focus on improving computational efficiency, real-time adaptability, and robustness to enhance the safety and reliability of autonomous driving systems.

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