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Editorial

Recent Advances in Motion Planning and Control of Autonomous Vehicles

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1. Introduction

An autonomous vehicle operates without human intervention, marking advancements in navigating structured urban roads and unstructured environments. Central to its operation are two pivotal components: planning and control. The planning module creates an open-loop trajectory, which lays out a spatiotemporal path for the ego vehicle to follow. The control module's role is to accurately follow this planned trajectory in a closed-loop manner and adeptly handle a spectrum of conditions ranging from varying road and weather situations to disruptive driving scenarios and even extending to abnormal circumstances, such as physical malfunctions and cyber threats. These modules are crucial because they embody the core intelligence of an autonomous system. This Special Issue aims to showcase the latest developments in planning and control strategies, which play critical roles in the evolution of autonomous vehicle technology.

Qualified submitted papers should focus on how the proposed planning and/or control method solves real-world problems. The editorial board would maintain a high standard in prescreening submitted drafts that are methodology oriented instead of task oriented. Notably, this Special Issue also welcomes papers that discuss methods indirectly related to planning and control as long as they facilitate the planning or control module. Topics of interest include but are not limited to the following:

- Path/trajectory/motion planning and replanning;
- Path/trajectory/motion control;
- On-road/off-road planning and control;
- Modeling and simulation methods for planning and/or control;
- Testing and validation methods related to planning and/or control;
- Safety-related issues with planning and control;
- Security-related issues with planning and control;
- Human–machine interaction related to planning and/or control;
- Intelligent techniques/methods for planning and/or control;
- Integration of planning and control;
- Reviews of planning or control methodologies;
- Data-driven/model-based planning or control;
- Comparisons among different types of planning or control methods;
- Fault-tolerant planning and control;
- Cooperative planning and control;
- Real-world applications of planning and control.

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The rest of this editorial paper is organized as follows. Section 2 briefly reviews the 11 papers published in this Special Issue. Section 3 presents our perspective, and Section 4 concludes the article.

2. Overview of Contributions

The first paper published in this Special Issue is titled Occlusion-aware Path Planning to Promote Infrared Positioning Accuracy for Autonomous Driving in a Warehouse. The paper proposes an occlusion-aware path planning method for autonomous vehicles in indoor environments and specifically addresses challenges in infrared positioning systems. In these systems, the vehicle, equipped with an infrared emitter, often faces signal occlusion issues due to obstacles, which can lead to inaccurate positioning if fewer than three receivers detect the signal. To tackle this issue, the study introduces a four-layered planner to enhance the accuracy of indoor infrared positioning by ensuring that the vehicle navigates areas with minimal occlusion while adhering to collision avoidance and kinematic constraints. The planner's effectiveness in reducing positioning errors and maintaining trackability is validated through simulations.

The second paper is titled A Path Planning Method for Underground Intelligent Vehicles based on an Improved RRT* Algorithm. This paper addresses the challenge of path planning for underground intelligent vehicles, with a particular focus on environments with complex drifts and vehicles with articulated structures (i.e., tractor–trailer vehicles). Recognizing the unique demands/features of underground scenarios, such as narrow, curved spaces without GPS, and the need for precise control due to the vehicles' complex kinematics, the study proposes an enhanced path planning method. This method is based on an improved version of the rapidly exploring random tree star (RRT*) algorithm and is tailored to meet the specific constraints of underground intelligent vehicles. The improvements to the RRT* algorithm include dynamic step size adjustment, steering angle constraints, and optimal tree reconnection strategies. These modifications aim to ensure that the path planning is efficient and compatible with the articulated structure of the vehicles and the challenging underground environment. The effectiveness of this improved algorithm is demonstrated through simulation case studies to showcase the improved algorithm's ability to generate paths with short lengths, few explored nodes, and high steering angle efficiency.

The third paper is titled A Hybrid and Hierarchical Approach for Spatial Exploration in Dynamic Environments. This paper introduces a novel, three-tiered hierarchical model called IRHE-SFVO for spatial exploration in dynamic environments and for addressing the challenge in AI system tasks, such as search and rescue. The model combines deep reinforcement learning for high-level exploration with a rule-based, real-time, obstacle-avoidance approach for local movement. It uses a global exploration module to identify distant, reachable targets for exploration and a local movement module that employs an optimistic A* algorithm and an improved finite-time velocity obstacle method for safe, efficient navigation. This approach results in smooth, natural movements and improved exploration efficiency, as demonstrated by tests on various 2D dynamic maps. The model's hierarchical structure simplifies training and enhances movement quality, marking an improvement over current spatial exploration techniques.

The fourth paper is titled Real-time Drift-driving Control for an Autonomous Vehicle: Learning from Nonlinear Model Predictive Control via a Deep Neural Network. This study focuses on developing a drift control method for autonomous vehicles and specifically addresses the challenge of managing oversteers in hazardous conditions, such as sharp curves or slippery roads. Initially, a nonlinear model predictive control (NMPC) method was designed to enable an autonomous vehicle to perform drift maneuvers. However, NMPC's reliance on real-time numerical optimization posed limitations in computational efficiency. To address this issue, the study introduces a deep neural network (DNN)-based controller trained using datasets generated from the NMPC method. This DNN-based controller effectively replaces NMPC; it reduces the computational load while maintaining similar control performance. The study's innovation lies in its successful integration of a data-driven approach into drift control. It demonstrates the DNN-based controller's capability to accurately track predefined trajectories under realistic simulation scenarios. This approach enhances real-time performance and has potential for broad applications in autonomous vehicle control, particularly in safety-critical situations.

The fifth paper is titled A Hybrid Asynchronous Brain–computer Interface Based on SSVEP and Eye-tracking for Threatening Pedestrian Identification in Driving. This paper introduces a multimodal hybrid brain–computer interface (BCI) system that integrates eye-tracking and electroencephalogram (EEG) signals to identify potentially threatening pedestrians in a driving context. Traditional steady-state visual evoked potential (SSVEP) BCIs in automatic driving can cause driver fatigue, so this study aims to improve interaction efficiency and reduce fatigue. The system works by superimposing stimulus arrows of different frequencies and directions on pedestrian targets, and subjects scan these arrows until they identify a threatening pedestrian. The hybrid BCI system distinguishes between active and idle states by using thresholds established in offline experiments, and subjects select pedestrians on the basis of their judgment in online experiments. This approach enhances selection accuracy by filtering low-confidence results. The system's effectiveness is demonstrated through experiments with six subjects. Its performance is superior to that of a single SSVEP-BCI system. It has an average selection time of 1.33 s, 95.83% accuracy, and an information transfer rate of 67.50 bits/min. This hybrid BCI system that combines eye tracking and SSVEP offers a promising solution for dynamic pedestrian identification in driving while enhancing safety and comfort.

The sixth paper is titled Space Discretization-based Optimal Trajectory Planning for Automated Vehicles in Narrow Corridor Scenes. The study addresses the challenge of optimal trajectory planning for automated vehicles in narrow corridor scenarios, a task characterized by limited space and the need for safe, feasible, and smooth navigation. The study introduces a novel space discretization-based optimal trajectory planning method that focuses on minimizing travel time and avoiding boundary collisions. The approach involves creating a mathematically described driving corridor model and a trajectory optimization model that incorporates various constraints, such as vehicle kinematics, collision avoidance, and actuator limitations, to ensure feasibility and comfort. The method's effectiveness is demonstrated through simulations and field tests, which show its superiority over baseline methods in terms of smoothness, computational efficiency, and reducing tracking errors.

The seventh paper is titled Trajectory Planning for an Articulated Tracked Vehicle and Tracking the Trajectory via an Adaptive Model Predictive Control. This study addresses the challenge of trajectory planning and tracking control for articulated tracked vehicles (ATVs), which are complex because of their unique steering mechanisms and nonlinear dynamics. The study introduces a two-step approach. First, the hybrid A-star method combined with minimum snap smoothing is employed for feasible kinematic trajectory planning. Second, an adaptive model predictive controller (AMPC) is implemented for precise trajectory tracking. The hybrid A-star method is selected for its effectiveness in generating smooth paths suitable for ATVs' nonholonomic nature, and the AMPC is designed to manage ATVs' nonlinearity through a linear-parameter-varying kinematic error-tracking model. This approach improves tracking accuracy and reduces computational load compared with standard model predictive controllers.

The eighth paper is titled GIS-data-driven Efficient and Safe Path Planning for Autonomous Ships in Maritime Transportation. This paper introduces a novel path planning method for autonomous ships and addresses the limitations of existing approaches that often disregard the dynamic constraints of ships, leading to impractical and inefficient trajectories. The proposed method, efficient and safe path planning (ESP), integrates ship dynamics into the planning process to generate real-time optimal trajectories that are fuel-efficient and smooth. ESP is distinct because of its threefold approach. First, it employs a modified A* search algorithm called A-turning to find an optimal path with minimal sharp turns by using geographic data from a geographic information system. Second, it formulates a minimum-snap trajectory optimization problem by incorporating dynamic ship constraints to ensure a smooth, collision-free trajectory with minimal fuel consumption. Last, ESP includes a local trajectory replanner based on B-spline for real-time avoidance of unexpected obstacles. The method's effectiveness is demonstrated through data-driven simulations, which show ESP's ability to plan safe global trajectories, minimize turning points, and reduce fuel consumption while swiftly adapting to avoid unforeseen obstacles.

The ninth paper is titled Micro-Factors-Aware Scheduling of Multiple Autonomous Trucks in Open-pit Mining via Enhanced Metaheuristics. The paper addresses the task of scheduling autonomous trucks in open-pit mines, which is complex because of the need for efficient coordination in dynamic environments. The study introduces a high-precision scheduling model that considers micro-level temporal and spatial factors to optimize the energy consumption, time, and output in the transportation system. Unique to this model is the inclusion of charging requirements for autonomous trucks, a critical aspect that is often overlooked in traditional scheduling. The methodological core of this research is the integration of a Voronoi diagram for accurately estimating the traverse average speed of each autonomous truck.

The tenth paper is titled Joint Dispatching and Cooperative Trajectory Planning for Multiple Autonomous Forklifts in a Warehouse: A Search-and-learning-based Approach. The paper explores the task of dispatching and cooperative trajectory planning for multiple autonomous forklifts in warehouse environments. Traditionally, dispatching and planning were treated as separate processes, leading to suboptimal motion quality in forklift teams. The study introduces a novel joint dispatching and planning method that simultaneously addresses these issues and aims to optimize cooperative trajectories. This method stands out because of its rapid execution, minimal computational demands, and high-quality solutions. It involves enumerating potential goals for each forklift and evaluating dispatch solutions by using an improved hybrid A* search algorithm enhanced with an artificial neural network for improved cost assessment. This approach ensures computational efficiency, kinematic feasibility, and collision avoidance and can rapidly find optimal solutions. The integration of neural networks into the dispatching process reduces the warehouse mission completion time by 2% compared with that in strategies without machine learning. The study highlights the importance of balancing shelf-filling states to prevent end-mission deadlocks and demonstrates that the proposed method allows forklifts to cooperatively find feasible trajectories quickly while maintaining efficiency even when priorities shift during tasks.

The eleventh paper is titled Tube-based Event-triggered Path Tracking for AUV against Disturbances and Parametric Uncertainties. The paper introduces a novel tube-based event-triggered path-tracking strategy to improve disturbance rejection in autonomous underwater vehicle (AUV) path tracking. The strategy combines a speed control law that uses linear model predictive control (LMPC) and a tube model predictive control (tube MPC) scheme. The LMPC controller is designed to reduce path-tracking deviation, and the tube MPC scheme calculates optimal control inputs, thus enhancing disturbance rejection. This approach considers AUVs' nonlinear hydrodynamic characteristics. It uses linear matrix inequality to establish tight constraints and a feedback matrix, both of which are calculated offline for real-time efficiency. An event-triggering mechanism adjusts these constraints based on surge speed changes, allowing for adaptive control. The strategy's effectiveness is demonstrated through numerical simulations, which show improved path-tracking performance and real-time capability. The paper addresses the challenge of robust control in AUVs in consideration of the complexities of underwater dynamics and the need for efficient, real-time solutions.

3. Emerging Trends and Perspectives

Based on the insights obtained from these papers, we anticipate several future trends in the field of autonomous driving planning and control.

Enhancing Efficiency in Planners for Tailored Autonomous Driving Scenarios

In autonomous driving, motion planning methods are broadly categorized into sampling-based [1], search-based [2], optimization-based [3], simulation-based [4], and learning-based [5] techniques. Each of these methodologies has its strengths and limitations. However, every real-world autonomous driving scenario presents distinct characteristics, necessitating specific task-related constraint design or trajectory preference design in motion planning formulation. Although various planner types are available for general applications, they often struggle to meet the specific needs of real-world scenarios. The autonomous driving research area, which has grown in the past decade, no longer gains substantial benefits from generic planners that do not effectively tackle real-world challenges. In the future, the development of motion planners is expected to increasingly focus on distinct and tangible scenarios. The emphasis is likely to shift toward devising solutions that are not only theoretically robust but also practically adept at addressing real-world issues in autonomous driving [6].

Leveraging Multimodal and Hierarchical Control Strategies

Future developments in autonomous driving are expected to increasingly focus on complex multimodal and hierarchical control strategies that can handle the dynamic and intricate nature of driving environments. The integration of deep learning's adaptability and advanced processing with the consistent reliability of rule-based methods is a promising direction. This integration can boost the adaptability and efficiency of autonomous driving systems, enabling them to effectively manage and adapt to changing conditions and complex tasks.

Enhancing Trajectory Planning Intelligence via Human–Machine Interaction

By integrating brain–computer interfaces and eye-tracking technologies, autonomous systems can now incorporate human input in various forms, such as human languages. This integration taps into the potential of cutting-edge fields, such as large language models, allowing for a dynamic and interactive driving experience. Such advancements mean that human drivers can assist autonomous systems through verbal commands or receive guidance through machine-interpreted human language, thus creating a collaborative and intuitive driving environment. This approach not only adds an extra layer of information to the decision-making process but also provides an additional safety net, making autonomous driving safe and aligned with human instincts and responses.

Re-evaluating the Role of Machine Learning in Autonomous Driving Planning

The integration of machine learning, particularly deep and reinforcement learning, is a growing trend in the field of autonomous driving motion planning. These methods, known for their ability to process and learn from large datasets, promise advancements in understanding and navigating complex and interactive driving environments. However, their current applications remain confined to simulations, with limited real-world deployment on real vehicles. This situation is partly due to the methods' generalization challenges; they sometimes act as supplementary tools relying on rule-based systems for core decision-making [7]. The true suitability of machine learning approaches for autonomous driving planning is a subject of ongoing research. A balance must exist between the innovative potential of these learning-based methods and the reliability of traditional rule-based approaches. This balance is crucial to developing practical, safe, efficient autonomous driving systems that can operate effectively in diverse and unpredictable real-world scenarios.

4. Conclusions

This Special Issue has successfully showcased a range of innovative approaches in the planning and control of autonomous vehicles by drawing insights from 11 groundbreaking papers. Our editorial has revisited these contributions, emphasizing their role in tackling real-world challenges and setting the stage for future advancements in autonomous driving. The collected papers highlight the shift toward highly specialized planning and control methods, the integration of complex control strategies, the enhancement of human–machine interaction, and the evolving application of machine learning in this dynamic field.

The field of autonomous driving is poised for considerable advancements. The focus on the development of planners and controllers that are effective in real-world scenarios marks a major progression. The incorporation of human input through advanced interfaces and the strategic use of machine learning techniques are redefining the capabilities of autonomous vehicles. These developments are not just technological achievements; they represent a shift toward highly intuitive, safe, and efficient transportation solutions.

Autonomous driving technology is filled with promise and potential. As we continue to innovate, the vision of safe, efficient, accessible transportation becomes increasingly realistic. This Special Issue not only captures the current state of the art but also serves as a guidepost for the future, where autonomous vehicles are expected to become an integral part of our daily lives by reshaping our approach to mobility and connectivity. The path forward is filled with excitement and endless possibilities. We are at the threshold of a new era in transportation driven by intelligence, adaptability, and a commitment to enhancing the human experience.

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