

## Editorial

# Editorial: Special Issue on Opportunities and Challenges with Autonomous Racing

In the ever-evolving landscape of autonomous vehicles, competition and research of high-speed autonomous racing emerged as a captivating frontier, pushing the limits of perception, planning, and control. Autonomous racing presents a setup where the intersection of cutting-edge software and hardware development sparks unprecedented opportunities and confronts unique challenges. The motorsport axiom, “If everything seems under control, then you are not going fast enough,” resonates in this special issue, underscoring the demand for algorithms and hardware that can navigate at the cutting edge of control, traction, and agility. In pursuing autonomy at high speeds, the racing environment becomes a crucible, pushing autonomous vehicles to execute split-second decisions with high precision.

Autonomous racing, we believe, offers a litmus test for the true capabilities of self-driving software. Just as racing has historically served as a proving ground for automotive technology, autonomous racing now presents itself as the crucible for testing self-driving algorithms. While routine driving situations dominate much of the autonomous vehicle operations, focusing on extreme situations and environments is crucial to support investigation into safety benefits. The urgency of advancing high-speed autonomy is palpable in burgeoning autonomous racing competitions like Formula Student Driverless, F1TENTH autonomous racing, Roborace, and the Indy Autonomous Challenge. These arenas provide a literal testbed for testing perception, planning, and control algorithms and symbolize the accelerating traction of autonomous racing as a proving ground for agile and safe autonomy.

Our special issue focuses on cutting-edge research into software and hardware solutions for high-speed autonomous racing. We sought contributions from the robotics and autonomy communities that delve into the intricacies of head-to-head multi-agent racing: modeling vehicle dynamics at high speeds, developing advanced perception, planning, and control algorithms, as well as the demonstration of algorithms, in simulation and in real-world vehicles. While presenting recent developments for autonomous racing, we believe these special issue papers will also create an impact in the broader realm of autonomous vehicles.

- The paper “An Autonomous System for Head-to-Head Race: Design, Implementation, and Analysis; Team KAIST at the Indy Autonomous Challenge” by Jung et al. presents a holistic overview of a complete software stack for autonomous racing. The authors detail the different perception, planning, and control modules to achieve high-speed autonomous driving. Ultimately, the software stack was deployed in the Indy Autonomous Challenge on a real-world autonomous racecar (Dallara AV-21) and achieved a velocity of 220 kph in a head-to-head autonomous race.

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- Saba et al. present a paper entitled “Fast and Modular Autonomy Software for Autonomous Racing Vehicles,” encompassing a detailed description of a system design for a full autonomous racing software stack as well as their experiences as participants of the Indy Autonomous Challenge. The paper highlights modular and low latency perception, a fast trajectory generation for following a race line and overtaking opponents, and a fast feedback-based controller. The authors demonstrate that their software stack could overtake at speeds up to 225 kph in a real-world autonomous racecar (Dallara AV-21) as part of a head-to-head autonomous race in the Indy Autonomous Challenge.
- The paper “er.autopilot 1.0: The Full Autonomous Stack for Oval Racing at High Speeds,” by Raji et al., is the third paper displaying research results from the Indy Autonomous challenge. The authors present a complete software stack consisting of perception, planning, and action modules. Additionally, the authors installed safety systems to detect anomalies in the system based on evaluating sensor signals. The software stack was deployed on a real-world autonomous racecar (Dallara AV-21) as part of the Indy Autonomous Challenge showcasing capabilities of high-speed autonomous driving on racetracks, including race line following, avoiding static obstacles, and performing active overtakes while reaching 270 kph.
- Ghignone et al. present a reinforcement learning (RL)-based approach in their paper entitled “TC-Driver: A Trajectory Conditioned Reinforcement Learning Approach to Zero-Shot Autonomous Racing,” used to control a small-scale autonomous racing vehicle. The authors develop a hybrid approach combining a model predictive control (MPC)-based controller with a trained RL agent to overcome imperfect modeling of parameters in the vehicle dynamics model of the MPC. While an optimal trajectory comes from classical approaches, the RL agent can track the trajectory under changing driving conditions and then overcome the shortcomings of classical controllers. The authors demonstrate their methods by running this hybrid approach on a small-scale F1TENTH autonomous vehicle and demonstrate that their approach has generalization capabilities on different racetracks.
- When it comes to head-to-head racing with overtaking maneuvers, planning interaction between the vehicles becomes a key component to success. The paper “Hierarchical Control for Head-to-Head Autonomous Racing” by Thakkar et al. introduces a realistic racing game formulation with safety and fairness rules. A high-level planner generates target waypoints using a simplified game representation, and a low-level controller computes precise control inputs based on these waypoints. Two hierarchical controllers are compared to baselines in simulation, demonstrating that the proposed methods, particularly one that uses multi-agent reinforcement learning at the low level, outperform alternatives regarding head-to-head race wins and rule adherence, showcasing competitive behavior even under complex racing conditions.
- And finally, extracting the full performance of autonomous controllers requires both the capture of complex vehicle dynamics and precise knowledge of the evolving tire-road interaction. The paper “A Hierarchical Adaptive Nonlinear Model Predictive Control Approach for Maximizing Tire Force Usage in Autonomous Vehicles,” by Dallas et al., discusses their efforts at a hierarchical adaptive nonlinear model predictive control for limit handling by adapting to changing tire-road conditions and maximally allocating tire force utilization. The evolving force potential at each tire is captured using first-order longitudinal load transfer dynamics and steady-state lateral weight transfer, which then facilitates optimal allocation of brake torque at each axle. Doing so now brings selected necessary chassis control functionality into the higher-level vehicle model that is then evaluated experimentally for enhanced performance. Together with an unscented Kalman filter for online friction estimation, this permits their full-scale vehicle to operate on a racetrack at up to 95% of maximum tire force usage.

The presented papers aim to offer valuable perspectives and inspiration to fellow roboticists, laying the groundwork for ongoing research. With ongoing competitions like F1TENTH, the Indy Autonomous Challenge, or the Abu Dhabi Racing League (A2RL), researchers worldwide can delve into the field of autonomous racing and present new solutions for high-speed autonomous driving.

Furthermore, since this unique field of autonomous vehicles is just starting, many open questions and unsolved problems exist. We hope that this special issue inspires more autonomy and robotics researchers to delve into the challenging and exhilarating arena created in autonomous racing.

Gratitude is extended to the dedicated reviewers who contributed profound insights and constructive feedback across multiple revisions. Special thanks are owed to the Editor-in-Chief, Sanjiv Singh, and Managing Editor, Sanae Minick, for their invaluable support throughout the editorial process of this special issue.

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