Ph.D. in Information Technology
Thesis Defenses

February 29th, 2024
at 17:00
Aula BIO 1, Building 21

Andrea TICOZZI – XXXVI Cycle

HIERARCHICAL TRAJECTORY PLANNING METHODS FOR AUTONOMOUS RACING DRIVERS

Supervisor: Prof. Sergio Matteo Savaresi

Abstract:

Head-to-head autonomous vehicle racing is quickly becoming a fundamental proving ground to test autonomous driving technologies at the limits of their capabilities. From control to state estimation, passing through perception, and trajectory planning, all the aspects of the driving algorithms are stressed in a challenging and competitive environment. In this context, several autonomous racing competitions, such as Formula Driverless, Roborace, and the Indy Autonomous Challenge, are becoming more and more popular, hence further pushing the research and development of this kind of technology.

In this dissertation, we focus on the development, analysis, and validation of trajectory planning algorithms for autonomous racing both on oval and road-course racetracks. We propose a hierarchical architecture, where the trajectory planning task is divided into three core steps: global planning, local planning, and trajectory segment generation. We frame each planning layer into state-of-the-art approaches, such as spatiotemporal graph-based planning, optimal control problems, or polynomial trajectory segment generation.

In particular, we first propose a novel global planning approach that aims at optimizing the ego driver's overtaking possibilities. By making use of a track-based occupancy grid framework, we will show how to learn the nominal path followed by the opponent; then, we use this information to plan a globally optimal plan through a graph-based search of possible overtaking paths along the track. The global plan must be then integrated with higher-rate local decisions. To this aim, we develop an overtaking-oriented local planning algorithm, which takes into account accurate opponent predictions to plan collision-free maneuvers in a spatiotemporal graph framework. The graph generation takes into consideration important aspects to guarantee competitiveness on the racetrack, such as traveling time minimization and tire-road friction saturation.

Concerning trajectory segment generation, we propose and analyze two different methods: a simpler polynomial-based path planning algorithm, focused on fast and reliable generation of smooth merging segments. Then, we propose a more complex Optimal Control Problem (OCP), which takes into account several elements, like positional constraints on the target path, together with curvature minimization objectives. Finally, we focus on the problem of computing optimal speed profiles for the generated segments, considering the three-dimensional features of the racetrack and other relevant vehicle dynamics aspects.

Finally, this work also includes a more general overview of the other core modules of the overall autonomous racing algorithm; we will provide some insight into the main challenges posed by the racing context to popular problems such as vehicle state estimation, trajectory tracking, and environment perception. All these aspects were first analyzed in simulation and then validated on a full-scale autonomous race car in single and multi-vehicle race scenarios, within the context of the Indy Autonomous Challenge competition.

Edoardo CATENARO – XXXVI Cycle

DATA-DRIVEN OPTIMIZATION OF PARAMETRIC CONTROLLERS IN VEHICLE APPLICATIONS

Supervisor: Prof. Sergio Matteo Savaresi

Abstract:

The increasing global demand for vehicles that balance driveability, safety, and eco-friendliness has driven the adoption of automatic controllers in vehicle modules, relying on sensors, actuators, and feedback control mechanisms. While many vehicle modules have matured in design and control, the optimal calibration of their parametric controllers remains a significant challenge due to system parameter variations, uncertainties, and complex dynamics involved. Within vehicle context, the goal of optimal parameter calibration is typically characterized with a system level black-box cost function that can only be assessed through expensive experiments. Such problem settings arise in various applications (e.g., electromechanical brake-by-wire actuator) where the considered system involves multi-physical domains (electric, mechanical, hydraulic) interacting with each other, as well as with the environment. Employing a model-based approach is particularly challenging, as it necessitates an accurate model of the complex system dynamics, which is both cost and time demanding. Furthermore, there is a risk of performance degradation due to system variability and model inaccuracies. In contrast, data-driven approaches provide an appealing solution by enabling direct controller parameter tuning based on measured data, bypassing the need for intermediate system model construction. Yet, this approach is not without its hurdles. These include the formulation of an apt cost function that captures the metrics of interest and ensures robustness to various operating scenarios. Additional concerns arise when the algorithm exploration policy must account for safety constraints, i.e., hard constraints avoiding unsafe testing. Specifically, the cautiousness of the sampling process is adjusted in order to avoid safety-critical operations. Eventually, handling instances where the cost function is non-evaluable represent a common scenario that needs to be tackled. Addressing all these challenges, especially as they relate to specific vehicle subsystems, continues to be an open topic in the current Literature.

This dissertation aims to bridge the gap between data-driven optimization methods and control parameter calibration in vehicle applications. Results on an industrial gear shifting management strategy for sport motorcycles constitute a novel contribution to this field. The novelties include designing a cost function capable of capturing relevant metrics – both at low- and system-level – aiming to derive a solution that is robust to scenario variations. Moreover, a comprehensive quantitative assessment is presented, including a comparison among state-of-the-art black-box tuning methodologies, e.g., Bayesian Optimization (BO) and set membership global optimization. Acknowledging the potential safety concerns during the sampling calibration process, an exploration policy ensuring – with high probability – control feedback stability is considered. Such a safety-oriented optimization framework is applied for the first time in an industrial case-study, specifically addressing the active mitigation of driveline oscillation in an electric vehicle through the implementation of a traction control strategy. While preserving optimality in terms of global cost minimization, safety-critical queries are significantly reduced with respect to state-of-the-art methods (e.g., BO, constrained-BO). Eventually, transitioning from a performance- to a preference-based optimization approach, this dissertation delves into scenarios where the cost function is unknown and non-evaluable. In such instances, decision-maker can only express a preference between calibration candidates. This approach is especially pertinent for tackling comfort-oriented optimization problems, where quantifying comfort remains subjective and challenging to mathematically model. The feasibility of the proposed framework – based on active preference learning – and its experimental validation is proved for the suspension calibration problem and represents its first application in the Literature. A learning methodology is introduced to accurately capture and incorporate driver pair-wise preferences. Lastly, a comparison with automatic performance-based suspension calibration approach via BO is proposed, guided by a driver-tailored performance metric, showing good agreement between the two techniques. The obtained results and improvements over the state-of-the-art are summarized as follows: (i) design, experimental validation, and assessment of a robust data-driven model-free auto-calibration framework for a gear-shift strategy in a sport motorcycle; (ii) design of a data-driven model-free safety-oriented calibration frame-work for an active damping controller in electric drivelines; (iii) design and experimental validation of an APL-based framework for addressing the suspension calibration problem, coupled with a novel learning methodology to extrapolate driver-tailored performance index. In essence, this thesis presents data-driven black-box approaches tailored to different vehicle applications, introducing innovative tools to assess their optimization quality and validation, thereby advancing data- driven calibration in the vehicle domain

PhD Committee

Silvia Strada, **Politecnico di Milano**
Matteo Massaro, **Università degli studi di Padova**
Antonio Ferramosca, **Università degli Studi di Bergamo**