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Computational optimization of a vehicle dynamic simulation model

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Background

The increasing reliance on simulation in motorsport has reshaped how teams prepare cars and drivers for competition. Modern race teams process massive amounts of telemetry—hundreds of sensors, producing terabytes of data each race—to optimize performance. High-fidelity simulators allow engineers to replicate real track conditions, test setup configurations, and minimize on-track testing costs. However, two fundamental challenges arise: (i) accurate hyperparameter optimization of the simulation model to ensure alignment with real-world data, and (ii) development of a virtual driver capable of realistically emulating human driving strategies. Hyperparameter optimization involves tuning parameters such as aerodynamic coefficients, tire dynamics, and engine maps to reduce mismatches between simulated and measured performance. This optimization problem is inherently large-scale, nonlinear, and computationally expensive, often requiring advanced simulation-based optimization (SBO) methods. Meanwhile, virtual drivers—traditionally based on PID or model predictive control—struggle to replicate the anticipatory, data-driven decisions of professional drivers. Data-enabled predictive control (DeePC) offers a promising alternative by directly exploiting trajectory data without relying on explicit system models. This doctoral project is positioned at the intersection of these challenges, aiming to develop robust optimization frameworks and data-driven control strategies that enhance both simulator fidelity and decision-making realism. By integrating optimization theory, control engineering, and collaboration with industrial partners such as Dallara Automobili S.p.A., the research seeks to advance the use of simulation in motorsport, reduce costs, and improve competitive advantage.

Project Goals

This research project has two interdependent goals. First, it seeks to design and validate an automated hyperparameter optimization pipeline for racecar simulation models. The objective is to systematically calibrate complex, high-dimensional parameter spaces using hybrid optimization algorithms that combine the exploratory power of Bayesian methods with the local refinement capabilities of Nelder-Mead search. The pipeline is expected to reduce the reliance on manual tuning, accelerate calibration processes, and ensure high correlation between simulated and real car performance. Second, the project aims to develop a virtual driver capable of replicating professional driving behaviors within the simulator. Unlike traditional approaches that rely on simplified control laws, the virtual driver will leverage DeePC to generate adaptive, data-driven trajectories under varying race conditions. Beyond technical targets, a strategic goal is to explore how innovations in simulation and driver modeling can be patented and commercialized, in collaboration with Bologna Business School. Taken together, these goals are intended to produce not only academic contributions but also practical tools for industry partners. Ultimately, the research aspires to bridge the gap between theoretical optimization and real-world motorsport engineering, leading to faster, more reliable simulators that drive competitive advantages in racing.

Experimental Approach

The methodology is structured around two main research axes. For hyperparameter optimization, the approach begins with benchmarking first-order optimization algorithms on synthetic test functions (e.g., Rosenbrock) to evaluate convergence rates and stability. Building on this analysis, a hybrid optimization algorithm was proposed, combining Bayesian optimization's global exploration with Nelder-Mead's local exploitation. This hybrid is applied to the racecar simulation model, where cost functions quantify the mismatch between simulated outputs and real telemetry data. To handle the computational burden of repeated simulation calls, surrogate modeling and dimensionality reduction techniques are incorporated. In parallel, the virtual driver development leverages DeePC, which bypasses explicit system modeling by learning input–output relationships directly from historical trajectory data. Experiments are carried out in a high-fidelity simulator co-developed with Dallara Automobili and in collaboration with Mälardalen University. The driver's ability to adapt to dynamic conditions such as tire degradation or weather variability is tested against both synthetic and real datasets. The research design includes iterative cycles of algorithm refinement, cross-validation against real race telemetry, and international collaboration for testing under different simulation environments. This dual-track experimental approach ensures that optimization improvements in model calibration directly enhance the realism and utility of the virtual driver.

Expected Outcomes

The project is expected to deliver several impactful outcomes. First, an automated hyperparameter optimization pipeline that outperforms manual and single-algorithm approaches in accuracy, robustness, and efficiency. The hybrid algorithm is anticipated to converge faster and adapt better to the nonlinear interdependencies of racecar models. Second, the development of a data-driven virtual driver will demonstrate the feasibility of DeePC in motorsport simulations, showing superior adaptability compared to PID and MPC-based approaches. The driver should be capable of generating optimal trajectories and dynamically adjusting control strategies to changing conditions. Together, these contributions will enhance simulator fidelity, reducing the gap between simulated and real-world performance, and enabling racing teams to optimize setups with fewer physical test sessions. Industrial collaborations are expected to validate these tools in practice, providing direct benefits to partners like Dallara Automobili. Beyond technical outcomes, the exploration of patenting strategies in collaboration with Bologna Business School may pave the way for commercialization pathways, ensuring that the developed methods are not only academically significant but also practically valuable in motorsport and potentially in broader domains of automotive engineering. Finally, the project will culminate in a comprehensive doctoral thesis and a portfolio of peer-reviewed publications, consolidating advances in computational optimization, control engineering, and simulation technology.

SUSTAINABLE DEVELOPMENT GOALS

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