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Doctoral Dissertation
Doctoral Program in Mechanical Engineering (37th Cycle)

Laboratory car testbed for single and multi-agent control: Testing of autonomous driving control algorithms using scaled vehicles

Candidate **Msc. Eugenio Tramacere** – Supervisors **Prof. Nicola Amati, PhD. Luis Castellanos**

Thesis Summary

This dissertation presents the conception, design, and experimental validation of a novel scaled-vehicle platform tailored for the testing of autonomous driving control algorithms. The research addresses a critical challenge in modern automotive engineering: how to bridge the gap between theoretical algorithm development and real-world deployment in a cost-effective and reproducible manner when dealing with autonomous vehicle control function development.

Full-scale autonomous vehicle testing is often prohibitive due to its high cost, risk, and logistical complexity. To mitigate these barriers, the research introduces a 1:10 scale vehicle platform that faithfully replicates the dynamics of full-size cars while enabling rapid, safe, and affordable experimentation. The primary goal is to create a modular, low-cost, and flexible testbed for real-time implementation of control strategies, including those for single- and multi-agent scenarios, while complying with automotive industry standards.

The proposed testbed integrates commercial RC cars with custom electronics, inertial sensors, and a vision-based localization system outboard the scaled vehicle, composed of 4 high-frequency cameras. A key architectural decision was to maintain non-intrusive sensing and actuation to preserve the original dynamic behavior of the vehicles. The vehicles interface with a centralized controller via CAN bus and ESP-NOW wireless communication, enabling accurate, real-time control and data acquisition. The system supports deployment of control algorithms written in MATLAB/Simulink directly onto real-time embedded ECU.

A key contribution of this work is the integration of nonlinear model predictive control (NMPC) strategies using the open-source Acados solver. This allows real-time

execution of optimization-based controllers, which are evaluated in various path-following and collision avoidance (CA) scenarios. Three distinct CA strategies are developed and benchmarked: (1) a heuristic sigmoid-based reference generator, (2) a nonlinear constraint approach based on a circular safety region, and (3) a probabilistic approach employing a stage-varying Gaussian confidence bound. The probabilistic method, which dynamically adjusts the safety margins during the prediction horizon, consistently demonstrated superior performance in terms of trajectory smoothness, dynamic feasibility, and safety margins, particularly in dynamic obstacle scenarios with respect to the other considered CA strategies.

Extensive experiments validate the effectiveness of the proposed architecture, showcasing its ability to bridge the gap between theoretical control formulations and practical deployment by offering a reproducible, scalable, and industry-compliant methodology for testing autonomous driving solutions in controlled environments. The testbed supports both single-vehicle and multi-agent experiments, making it suitable for research on cooperative and distributed driving strategies. In conclusion, the insights gained contribute toward the broader objective of safe and reliable autonomous mobility, particularly in constrained or cost-sensitive development phases.

Keywords: *Autonomous vehicle, Testing, Scaled-vehicle, NMPC, Collision Avoidance*