

Praxis der Forschung

Sampling-Based Model Predictive Control for Motion Planning

Methods for Big Data, Scientific Computing Center

Advisor

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Examiner

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Possible Start

As soon as possible

Background

Model Predictive Control (MPC) is a widely used framework for motion planning and decision making in autonomous driving. Classical MPC approaches typically formulate motion planning as a nonlinear optimization problem subject to vehicle dynamics, safety constraints, and prediction models of surrounding traffic participants. While optimization-based formulations can provide structured solutions and enable the incorporation of domain knowledge, they often become computationally challenging in highly nonlinear or multi-modal planning scenarios.

Recent advances in robotics and model-based reinforcement learning have demonstrated the effectiveness of **sampling-based MPC** methods such as the **Cross-Entropy Method (CEM)**, and **Model Predictive Path Integral (MPPI)** control. Instead of solving an optimization problem using gradients or numerical solvers, these methods generate and evaluate large numbers of candidate trajectories through stochastic sampling. Sampling-based methods naturally support non-convex objectives, black-box models, and parallel execution, making them attractive for the application on hardware accelerators. However, a key limitation of existing approaches is that they typically assume unimodal Gaussian distributions over control inputs. Motion planning and behavior prediction in autonomous driving are inherently **multi-modal**: multiple plausible maneuvers often exist simultaneously, such as changing lanes to the left or right, yielding at an intersection, or overtaking a slower vehicle. Maintaining these discrete maneuver hypotheses within a sampling-based MPC framework remains an open research challenge.

The goal of this thesis is to investigate, implement, and evaluate sampling-based MPC algorithms for autonomous driving and to extend these approaches using **mixture-based uncertainty models** that represent multiple maneuver hypotheses. The work can be conducted using an **existing research software stack** in **Python, PyTorch and CasADI**, containing baseline MPC implementations, a simulation environment with NuPlan scenarios, and evaluation pipelines for benchmark, long-tail, and OOD performance assessment.

Task Details

- Conduct a literature review on sampling-based MPC, including random shooting, Cross-Entropy Method (CEM), MPPI or related approaches.
- Implement and evaluate at least two sampling-based MPC baselines within the existing planning framework.
- Compare sampling-based approaches against existing optimization-based MPC methods with respect to planning quality, computational efficiency, robustness, and convergence behavior.
- Extend the sampling distributions using Gaussian mixture models to represent multi-modal motion predictions and maneuver hypotheses.
- Systematically evaluate the proposed approaches on representative autonomous-driving scenarios and analyze strengths, limitations, and future research directions.