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Real-Time Nonlinear Model Predictive Control: Efficient Methods for Domain Reduction

By

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Nonlinear Model Predictive Control (NMPC) is an advanced control method, based on the online solution of a suitable optimal control problem (OCP). However, this operation may require high computational costs, which can compromise the use of NMPC in “fast” real-time applications.

To address this challenge, the thesis introduces two novel NMPC approaches, called Dimensionality Reduction and Side-length Reduction, designed to reduce the computational burden by minimizing the volume of the search domain. Both approaches comprise two phases: (i) offline data generation and preprocessing; (ii) online optimization. In the Dimensionality Reduction approach, the offline phase leverages gradient computation and nonlinear sparse identification techniques. In particular, the gradient computation is used to detect the directions of greatest variability of the optimization problem. This is accomplished by identifying the decision variables that exert the most significant influence on the OCP, called the most relevant decision variables. Subsequently, a nonlinear sparse identification technique is used to approximate from data the NMPC control law. During the online optimization phase, this approximation is exploited to provide a good starting point for the optimization algorithm. Furthermore, the OCP is exclusively performed on the most relevant decision variables, while for the less important ones, the values obtained from the approximation are used. On the other hand, the Side-length Reduction approach employs a Set Membership method to derive tight guaranteed bounds on the relevant decision variables during the offline phase, which are then used to effectively shrink the search space during the online optimization. These two approaches aim to reduce the number of decision variables and the size of the search domain, thereby significantly improving computational efficiency.

A comprehensive theoretical analysis is conducted to investigate the inherent computational complexity of the proposed methods, demonstrating how dimensionality and side-length reductions can decrease the number of mathematical operations required in a nonlinear optimization algorithm and improve its convergence rate. The theoretical findings are complemented by an

extensive numerical analysis, where the proposed methods are tested on three realistic autonomous driving scenarios: lane keeping on urban roads, obstacle avoidance on rural roads, and parallel parking. These scenarios were chosen to showcase the versatility of the proposed methods in handling different tasks from simple lane keeping to complex maneuvers involving dynamic obstacles.

Performance evaluations compare the proposed methods with respect to standard NMPC approaches using both Software-In-the-Loop (SIL) and Hardware-In-the-Loop (HIL) simulations. The SIL simulations are conducted using Simulink, employing both Sequential Quadratic Programming (SQP) and Particle Swarm Optimization (PSO) algorithms to demonstrate the effectiveness of the methods across different optimization techniques. The HIL simulations involve implementing the NMPC algorithm on an NVIDIA Jetson Nano board, focusing on real-time performance. The results indicate that the proposed strategies achieve significant reductions in computation time without compromising the quality of the solutions. These methods demonstrate robustness and versatility, being adaptable to a wide range of optimization algorithms and real-time control applications.