

Abstract

Model Predictive Control (MPC) is an advanced optimal control strategy, widely recognized for its remarkable versatility in controlling a wide range of nonlinear, multivariable dynamical systems, and explicitly handling constraints.

Despite its desirable features, the application of MPC faces some inherent limitations in practice. The first is real-time feasibility, as MPC requires to repeatedly solve an optimal control problem online, which entails a considerable computational effort, compromising its use in fast application scenarios. The second concerns the lack, in existing MPC formulations, of a systematic methodology to handle multiple, conflicting, and time-varying control objectives, which typically arise in several practical applications.

This thesis aims to address these two challenges by proposing novel theoretical and methodological MPC frameworks, capable of operating in real time, under strict timing constraints and limited computational resources, while also extending their formulation to handle multiple, potentially conflicting control objectives, ensuring consistent performance and systematic closed-loop stability guarantees.

To address the challenge of real-time feasibility, we pursue two different directions. The first one focuses on developing a comprehensive analytical framework to fast solve Nonlinear MPC (NMPC) problems in the Koopman lifted space. Leveraging the Koopman operator theory, we propose a general procedure to analytically represent NMPC problems in a higher-dimensional Koopman space, and a complementary method to arbitrarily reduce the dimensionality of such a lifted space, which can be, in some cases, infinite-dimensional. This strategy yields an equivalent quadratic program (QP) in the Koopman lifted space (called Koopman NMPC, or K-NMPC), that closely approximates the original NMPC solution and can be solved with reduced computational effort. The K-NMPC framework showcases proficient control performance and a ten-fold reduction in computation times, as confirmed through extensive simulations and experimental validations.

The second direction achieves fast MPC operation through direct hardware implementation. Specifically, we present a general methodology to design fully-analog electronic circuits implementing Linear-Quadratic MPC policies (QP-MPC), leveraging Explicit MPC (Ex-MPC). This approach, referred to as Analog Circuitual Ex-MPC, eliminates the need for online optimization on digital hardware, and ensures a remarkably fast evaluation of the MPC control action, with computation times in the order of few microseconds. This methodology is validated on the control of DC-DC Buck converters, a class of electronic devices with an inherently fast dynamics, demonstrating its real-time feasibility, robustness, and solid control performance.

To address the second challenge, we first direct our efforts towards Economic Nonlinear MPC (E-NMPC), a noteworthy variant of classic NMPC for systems where achieving a profitable economic performance is of primary concern. However, a conflict between control tasks naturally arises if the system is also tasked with regulation or tracking objectives. In this context, we propose a novel E-NMPC formulation, capable of handling such conflicting objectives, together with a general constructive procedure to guarantee closed-loop stability with minimal impact on the economic performance. This framework is validated on the case study of adaptive cruise control (ACC) for electric vehicles, achieving the optimal trade-off between vehicle control performance and energy efficiency, while also ensuring closed-loop stability.

For handling conflicting control tasks, we also propose an alternative framework, called Neural Adaptive Model Predictive Control (NA-MPC). NA-MPC extends standard MPC formulations by introducing an online metaheuristic tuning strategy, which dynamically adapts the weights of the MPC cost function, to achieve multiple conflicting objectives concurrently, and a neural emulation of the MPC policy, providing an equivalent neural controller that exhibits negligible computation time. The NA-MPC framework is applied to the case study of power management in fuel cell hybrid electric vehicles (FCHEVs), demonstrating solid control performance, adaptability, and superiority over conventional strategies.