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Model predictive control of nonlinear singularly perturbed systems: Application to a large-scale process network

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ABSTRACT

This work focuses on model predictive control of nonlinear singularly perturbed systems. A composite control system using multirate sampling (i.e., fast sampling of the fast state variables and slow sampling of the slow state variables) and consisting of a "fast" feedback controller that stabilizes the fast dynamics and a model predictive controller that stabilizes the slow dynamics and enforces desired performance objectives in the slow subsystem is designed. Using stability results for nonlinear singularly perturbed systems, the closed-loop system is analyzed and sufficient conditions for stability are derived. A large-scale nonlinear reactor-separator process network which exhibits two-time-scale behavior is used to demonstrate the controller design including a distributed implementation of the predictive controller.

1. Introduction

Chemical processes and plants are characterized by nonlinear behavior and strong coupling of physico-chemical phenomena occurring at disparate time-scales. Examples include fluidized catalytic crackers, distillation columns, biochemical reactors as well as chemical process networks in which the individual processes evolve in a fast time-scale and the network dynamics evolve in a slow time-scale. Singular perturbation theory provides a natural framework for modeling, analysis, order reduction and controller design for nonlinear two-time-scale processes (e.g., [1,2]). Within this framework, methods for controller design based on optimal control (e.g., [3]), geometric control (e.g., [1,2]) and Lyapunov-based control [4] have been developed.

Model predictive control (MPC) is a practically important control framework which can be used to design and coordinate control systems and can explicitly handle input and state constraints. MPC utilizes a model to predict the future evolution of the plant at each sampling time according to the current state over a given prediction horizon. MPC utilizes these predictions in an on-line optimization framework to obtain an optimal control input trajectory which minimizes an objective function subject to state and input constraints. To reduce the dimensionality and computational burden of the optimization problem, optimization is performed over the set of piecewise constant trajectories with fixed sampling time and finite prediction horizon. Once the optimization problem is solved, only the first step of the optimal input is implemented by the actuators, the rest of the trajectory is discarded and the optimization is repeated in the next sampling step (e.g., [5,6]). In [7], a Lyapunov-based MPC (LMPC) design was proposed by incorporating a Lyapunov function based constraint in the MPC optimization problem to guarantee the closed-loop stability. This LMPC design inherits the stability properties of a pre-existing Lyapunov-based controller and has an explicitly characterized stability region. In the context of control of large-scale process networks within a centralized MPC framework, the computational complexity of MPC may increase significantly with the increase of the number of state variables and manipulated inputs. Moreover, a centralized control system for large-scale systems may be difficult to organize and maintain and is vulnerable to potential process faults. To overcome these issues, distributed MPC (DMPC) can be utilized. In a DMPC framework, optimal input trajectories are obtained by solving a number of lower-dimension MPC problems compared to the fully centralized MPC (see, e.g., [8–10]). In the context of MPC of singularly perturbed systems, most of the efforts have been dedicated to linear systems [11] or to MPC of specific classes of two-time-scale processes [12,13].

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