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Economic Model Predictive Control: Handling Valve Actuator Dynamics and Process Equipment Considerations

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Contents

Economic Model Predictive Control: Handling Valve Actuator Dynamics and Process Equipment Considerations

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ABSTRACT

Chemical process equipment (e.g., sensors, valves, pumps, and vessels) can impact the dynamics, profitability, and safety of plant operation. While continuous chemical processes are typically operated at steady-state, a new control strategy in the literature termed economic model predictive control (EMPC) moves process operation away from the steady-state paradigm toward a potentially time-varying operating strategy to improve process profitability. The EMPC literature is replete with evidence that this new paradigm may enhance process profits when a model of the chemical process provides a sufficiently accurate representation of the process dynamics. Recent work in the EMPC literature has indicated that though the dynamics associated with equipment are often neglected when modeling a chemical process, they can significantly impact the effectiveness

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of an EMPC (and the potentially time-varying operating policies dictated by an EMPC may impact equipment in ways that have not been previously observed under steady-state operating policies); therefore, equipment dynamics must be accounted for within the design of an EMPC. This monograph analyzes the work that has accounted for valve behavior in EMPC to date to develop insights into the manner in which equipment behavior should impact the design process for EMPC and to provide a perspective on a number of open research topics in this direction.

Keywords: valve stiction, valve nonlinearities, economic model predictive control, process control, process safety, process equipment

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Introduction

The limitations of process equipment (e.g., catalysts, valves, pumps, compressors, heat exchangers, vessels, and sensors), and the manner in which the materials that comprise such equipment change over time, have long been understood to pose issues for chemical process control and therefore have been accounted for in various ways. In the commonly utilized optimization-based controller known as model predictive control (MPC) (Qin and Badgwell, 2003), valve limitations are often accounted for within the control design by setting bounds on the manipulated inputs as constraints (Rawlings, 2000). Issues associated with sensors (e.g., drift and bias) have been accounted for in process control utilizing techniques such as measurement replacement (Kettunen *et al.*, 2008) and output compensation (Prakash *et al.*, 2002). Actuator faults (Venkatasubramanian *et al.*, 2003; Gajjar and Palazoglu, 2016) have been handled through reconfiguration of MPC designs (Mhaskar, 2006; Alanqar *et al.*, 2017c; Lao *et al.*, 2013). Because such equipment limitations have been recognized to play an important role in the effectiveness of MPC designs and in maintaining closed-loop stability and process operational safety, developments in economic model predictive control (EMPC) (Ellis *et al.*, 2014a; Rawlings *et al.*, 2012; Müller *et al.*, 2015; Amrit *et al.*, 2013; Limon *et al.*, 2014), which is an MPC with a modified objective function (compared to the traditional industrial design) that does not take its minimum at a process steady-state and therefore may operate a process in a time-varying fashion, can incorporate similar techniques. The methods for accounting for equipment limitations just described are handled at the design stage of MPC/EMPC when it is still possible to add appropriate constraints and abilities for model updating or controller reconfiguration to the control system.

Despite recognition of the importance of accounting for equipment limitations like hard bounds and equipment failure in MPC and EMPC, little emphasis has been placed on accounting for equipment behavior in a dynamic context. Though it could be argued that the traditional methods utilized for model updating in MPC based on process data (Marlin and Hrymak, 1996) and data-based on-line model update methods for EMPC (Alanqar *et al.*, 2017b) can account for time-varying process dynamics attributable to equipment issues such as catalyst deactivation and heat exchanger fouling, these methods do not explicitly analyze the dynamic behavior of equipment to understand how it may, like other limitations/failure mechanisms of equipment, imply that adjustment may need to be made to MPC/EMPC designs at the design stage. Several works on MPC accounting for valve behavior through various constraints (e.g., Zabiri and Samyudia, 2006; del Carmen Rodríguez Liñán and Heath, 2012) have appeared. However, these have not taken the dynamic behavior of the valves explicitly into account in the dynamic model utilized for making state predictions. Srinivasan and Rengaswamy (2008) explored a compensation method for valve stiction in which a compensating signal to be added to the output of a linear controller for a process is computed by an optimization problem with a model that includes a data-driven stiction model (it is EMPC-like, taking advantage of a prediction horizon to compute a number of compensating signals throughout this horizon and only applying the first). Several recent works (e.g., Durand *et al.*, 2017; Durand and Christofides, 2016; Bacci di Capaci *et al.*, 2017) have focused on explicitly accounting for the dynamic behavior of valves in MPC/EMPC. It has been demonstrated that in addition to updates to the model utilized for making state predictions in MPC/EMPC to handle the valve behavior, adjustments may also need to be made to the design itself, incorporating different constraints than in the case that the valve dynamics can be neglected. Furthermore, the time-varying nature of the input trajectories that may be set up under an EMPC may cause equipment considerations to become relevant that may not have been previously observed when steady-state tracking was the operational goal.

Motivated by these recent developments indicating that accounting for dynamic valve behavior in control design can be critical to the success of an MPC/EMPC formulation, we focus in this work on analyzing the literature related to valve behavior in EMPC to bring to the forefront the notion that despite the general trend in the literature toward neglecting equipment behavior, equipment behavior should be accounted for within EMPC at the design stage. Using the literature focused on accounting for valve behavior in EMPC as a guide, we highlight the necessity of accounting for equipment behavior in EMPC from an economics and a constraint satisfaction viewpoint and also indicate that it may not be possible to develop EMPCs without accounting for equipment behavior and then expect that all results will readily translate to the case with equipment behavior accounted for in the model utilized for making state predictions. To demonstrate this, we select several recent EMPC developments which have not explicitly considered process-valve or process-equipment systems within the design, and suggest that the relevant dynamics of process-equipment systems may not fit within the traditional set of assumptions developed when equipment behavior is neglected. Therefore, equipment behavior must be considered from the start of EMPC design; if it is not, it may be necessary to assess whether developments in the literature can be directly applied to practical systems in which equipment plays a role before utilizing such designs.

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