Journal of Process Control 54 (2017) 1–13

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Offset-free multi-model economic model predictive control for changing economic criterion

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ARTICLE INFO

Article history:
Received 3 June 2016
Received in revised form 6 February 2017
Accepted 24 February 2017

Keywords:
Economic MPC
Multi-model uncertainty
Offset-free
Stability

ABSTRACT

Economic Model Predictive Controllers, consisting of an economic criterion as stage cost for the dynamic regulation problem, have shown to improve the economic performance of the controlled plant. However, throughout the operation of the plant, if the economic criterion changes – due to variations of prices, costs, production demand, market fluctuations, reconciled data, disturbances, etc. – the optimal operation point also changes. In industrial applications, a nonlinear description of the plant may not be available, since identifying a nonlinear plant is a very difficult task. Thus, the models used for prediction are in general linear. The nonlinear behavior of the plant makes that the controller designed using a linear model (identified at certain operation point) may exhibit a poor closed-loop performance or even loss of feasibility and stability when the plant is operated at a different operation point. A way to avoid this issue is to consider a collection of linear models identified at each of the equilibrium points where the plant will be operated. This is called a multi-model description of the plant. In this work, a multi-model economic MPC is proposed, which takes into account the uncertainties that arise from the difference between nonlinear and linear models, by means of a multi-model approach: a finite family of linear models is considered (multi-model uncertainty), each of them operating appropriately in a certain region around a given operation point. Recursive feasibility, convergence to the economic setpoint and stability are ensured. The proposed controller is applied in two simulations for controlling an isothermal chemical reactor with consecutive-competitive reactions, and a continuous flow stirred-tank reactor with parallel reactions.

1. Introduction

The main goal of advanced control strategies is to operate the plants as close as possible to the economically optimal operation point, while ensuring stability. In the process industries, this objective is achieved by means of a hierarchical control structure [28,11]: an economic optimization level – usually referred as Real Time Optimizer (RTO) – sends the economically optimal setpoints to an MPC layer, which calculates the optimal control action to be sent to the plant, in order to regulate it as close as possible to the setpoint, taking into account a dynamic model of the plant, constraints, and stability requirements [23,31].

The time-scale separation between the RTO and MPC layers that this hierarchical control scheme produces has two main consequences on the economic performance of the plant. The first one is that the economic setpoint calculated by RTO may be inconsistent or unreachable with respect to the dynamic layer [17]. A solution to this issue is to add a new optimization level in between of RTO and MPC, referred as the steady state target optimizer (SSTO). The SSTO calculates the steady state to which the system has to be stabilized, solving a linear or quadratic programming and taking into account information from the RTO and the linear model used in the MPC [29,34,21].

The second consequence is produced by the way the MPC controller is designed. Usually the MPC control law is designed to ensure asymptotic tracking of the setpoint, without taking into account the issue of transient costs [5]. This way to operate, which is practically optimal when the setpoint does not change with respect to the dynamic of the system, may provide poor economic

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http://dx.doi.org/10.1016/j.jprocont.2017.02.014

performance in those applications (usually characterized by frequent changes in the economic criterion) for which the cost in the transient is more significant than the cost at the steady state. Economic MPC [30] is the solution proposed in the last few years to overcome these drawbacks.

Different ways to approach this control problems have been proposed in literature: Dynamic Real Time Optimizer (D-RTO) [9,17,33] solves a dynamic economic optimization and delivers target trajectories (instead of target steady state) to the MPC layer; the one-layer MPC strategies integrate the RTO economic cost function as a stationary part of the MPC cost function [1,35,2]; Economic MPC considers the nonlinear economic cost of the RTO as the stage cost of the dynamic regulation problem. This method has been widely studied in the last few years, and Lyapunov stability has been proved for different cases [9,16], resorting to strong duality assumptions [10,12], and to dissipativity assumptions [5,3,15,24].

From a practical point of view, the economic criterion to be minimized may vary during the operation of a plant, for both: (i) market fluctuations, which may cause changes in the cost function and in the prices that parameterize this function, and (ii) variations in disturbances estimation or constraints, due to data reconciliation algorithms. Thus, EMPC formulations characterized by either time-varying or parameter-varying stage costs seem to be more suitable [6,7,12].

In general, in industrial applications, a nonlinear description of the plant may not be available, since identifying a nonlinear plant could be a very difficult task. On the other hand, the methods for the identification of linear models are very easy to implement, and are common practice in industries. For this reason, MPC controllers are designed using a linear model, which may not represent the behavior of the plant in all its operation points. For the case of petrochemical processes, for instance, the plant to be controlled is nonlinear, but has sparse operation points with different economic behaviors. The nonlinear behavior of the plant makes that the controller designed using a linear model (identified at certain operation point) may exhibit a poor closed-loop performance or even loss of feasibility and stability when the economically optimal operation point is changed. A convenient form of representing these plant-model uncertainties is by considering a finite family of linear models identified at each of the equilibrium points where the plant will be operated. This way, each operating point allows one to obtain a linear model sufficiently accurate to describe the system, and which operates appropriately in a certain region around such equilibrium point. Furthermore, since not many operating points are considered in the operation of this kind of systems, only few linear models could be required to describe the complete operation of the plant. This approach, called multi-model description of the plant, is a formulation of robust MPC which has shown to be of interest from a theoretical point of view [8,14,13,22] as well as for practical implementation [28].

In this work, the economic MPC for changing economic costs presented in [12], has been extended to the case of a multi-model representation of the plant and offset-free estimation. To this aim, a finite family of linear models is obtained, which describes the behavior of the plant to be controlled, in different operation points. These points are economically optimal steady states for the plant under a certain choice of the economic criterion. Following the idea of [8], the models are required to share the same applied control actions and a contractive constraint is imposed. However, to the aim of reducing conservativeness, the models are required to have only a few control actions (in the optimal control) equal to each other, while the remaining controls in the sequence are free degrees of freedom for each model. Recursive feasibility, stability and convergence to the optimal operation point are always ensured, no matter which model of the family represents the true plant.

The proposed controller is applied in two simulations for controlling an isothermal chemical reactor with consecutive-competitive reactions, and a continuous flow stirred-tank reactor with parallel reactions. The results of such simulations show how the multi-model approach ensures feasibility and stability when the economically optimal operation point changes, as well as better economic performance than nominal offset-free controllers.

The work is organized as follows. In Section 2 the problem is stated. In Section 3 the proposed multi-model Economic MPC is presented. In this section, Lyapunov stability of the proposed controller is proved, and its main properties are presented. Finally, illustrative examples and conclusions of this study are provided in Sections 4 and 5.

2. Problem statement

Consider a system described by an nonlinear discrete time-invariant model

$$x_p^+ = f(x_p, u) \tag{1}$$

where $x_p \in \mathbb{R}^n$ is the measured state of the plant to be controlled, $u \in \mathbb{R}^m$ is the current control vector, and x_p^+ is the successor state. Function $f(x, u)$ is assumed to be continuous and differentiable at any equilibrium point. The solution of this system for a given sequence of control inputs $\mathbf{u}$ and initial state x_p is denoted as $x_p(j) = \phi(j; x_p, \mathbf{u})$ where $x_p = \phi(0; x_p, \mathbf{u})$. The state of the system and the control input applied at sampling time k are denoted as $x_p(k)$ and $u(k)$ respectively. The system is subject to hard constraints on state and control:

$$x_p(k) \in \mathcal{X}, \quad u(k) \in \mathcal{U} \tag{2}$$

for all $k \geq 0$.

Assumption 1. $\mathcal{X}$ and $\mathcal{U}$ are convex and compact, and both sets contain the origin in their interior.

The steady-state conditions of the plant (x_s, u_s) are such that (1) is fulfilled, i.e.

$$x_s = f(x_s, u_s) \tag{3}$$

Consider now, a nonlinear function $f_{eco}(x, u, \rho)$ that is a measure of the economic objectives of the plant. The parameter ρ describes prices, costs or production goals, that might be varying during the operation of the plant. This parameter has to be considered as an input to the RTO layer, resulting from the economic scheduling and planning, and may be time-varying due to market fluctuations or data reconciliation. Thus, let us define the RTO problem as follows:

Definition 1. The optimal operation of the plant is given by the steady state (x_s, u_s), which satisfies

$$(x_s, u_s) = \arg\min_{(x,u)} f_{eco}(x, u, \rho) \tag{4}$$

$$\begin{aligned} s.t. \quad & x \in \mathcal{X}, \qquad u \in \mathcal{U} \\ & x = f(x, u) \end{aligned}$$

Notice that the optimal operation point depends on the value of ρ, that is $(x_s(\rho), u_s(\rho))$. However, for the sake of clarity, in what follows, we will use the notation (x_s, u_s).

Assumption 2. The cost $f_{eco}(x, u, \rho)$ is locally Lipschitz continuous in (x_s, u_s); that is there exists a constant $\Gamma > 0$ such that,

$$|f_{eco}(x, u, \rho) - f_{eco}(x_s, u_s, \rho)| \leq \Gamma |(x, u) - (x_s, u_s)|$$

for all ρ and all $(x, u) \in \mathcal{X} \times \mathcal{U}$ such that $|x - x_s| \leq \varepsilon$ and $|u - u_s| \leq \varepsilon$, $\varepsilon > 0$.