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Sensitivity analysis for selective constraint and variability tuning in performance assessment of industrial MPC

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Abstract

This paper is concerned with economic performance assessment of industrial model predictive control (MPC) applications for processes with constraints. The interest of this paper is to find sensitive process variables, which are the most contributive to the economic performance of MPC. Optimization algorithms for sensitivity analysis are presented for both constraint and variability tuning of industrial MPC applications. Several new problems related to sensitivity properties of process variables, which arise in the actual MPC economic performance assessment, are addressed. Industrial case studies are included to demonstrate how the proposed sensitivity analysis can be used to provide practical and selective tuning guidelines in industry.

Keywords: Model predictive control; Economic performance assessment; Sensitivity analysis; Constraint tuning; Variability tuning; Convex optimization

1. Introduction

Successful implementations of model predictive control (MPC) can now be seen in a wide variety of industrial application areas, which include pulp and papers, refinery, petrochemical, bio-tech industries, food processing, air and gas plants, power, etc., due to its capabilities and appealing advantages, such as economic optimization, constraints handling, accurate trajectory tracking control, etc. It has been demonstrated as one of the most effective and widely used advanced process control strategies to deal with multivariable systems with input and output constraints. It computes a sequence of predictive manipulated variable (MV) adjustments that optimize the future behavior of a plant with constraints and, among the optimal control moves, only the first one is adopted as the current control law. A receding horizon strategy then applies on-line to repeat the procedure with new measurements obtained from the system at the next sample time. Regarding innovative advancements of this algorithm and its applications, there has been a large amount of work in the literature including survey articles and books (Camacho & Bordons, 1998; Kwon & Han, 2005; Maciejowski, 2002; Morari & Lee, 1999; Qin & Badgwell, 2003; Rawlings, 2000). Actually, in industries, MPC technology products have been developed by several venders and implemented to many industrial process units (Kassmann, Badgwell, & Hawkins, 2000; Krishnan, Kosanovich, DeWitt, & Creech, 1998; Sorensen & Cutler, 1998); see the recent industrial MPC survey paper (Qin & Badgwell, 2003). On the other hand, it is noted that less effort has been made on the performance assessment of existing constrained MPC applications, while the performance assessment of conventional unconstrained controllers has been well studied such as in Harris (1989), Harris, Boudreau, and Macgregor (1996), Huang, Shah, and Kwok (1997), Huang and Shah (1999), Xu, Lee, and Huang (2006), Choudhury, Shah, Thornhill, and Shook (2006), Jelali (2006), Salsbury (2007), Srinivasan, Rengaswamy, and Miller (2007) and Bauer and Craig (2008).

The MPC scheme has been used to maneuver processes closer to their physical limits in order to obtain a better economic performance according to the external market

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Nomenclature

J	economic objective function
$a_{y,i}(k)$	quadratic economic coefficient for ith CV at sample time k
$b_{y,i}(k)$	linear economic coefficient for ith CV at sample time k
$a_{u,j}(k)$	quadratic economic coefficient for jth MV at sample time k
$b_{u,j}(k)$	linear economic coefficient for jth MV at sample time k
$L_{y,i}(k)$	low limit of ith CV
$H_{y,i}(k)$	high limit of ith CV
$L_{u,j}(k)$	low limit of jth MV
$H_{u,j}(k)$	high limit of jth MV
$\alpha_{y,i}(k)$	half of constraint range of ith CV
$\alpha_{u,j}(k)$	half of constraint range of jth MV
$\sigma_{y,i}$	standard deviation of ith CV
$\sigma_{u,j}$	standard deviation of jth MV
v_i	percentage of variability change of ith CV
$\lambda_{y,i}$	percentage of low limit change of ith CV
$\lambda_{u,j}$	percentage of low limit change of jth MV
$\mu_{y,i}$	percentage of high limit change of ith CV
$\mu_{u,j}$	percentage of high limit change of jth MV
$\underline{v}_i$	lower bound of v_i
$\overline{\lambda}_{y,i}$	upper bound of $\lambda_{y,i}$
$\overline{\lambda}_{u,j}$	upper bound of $\lambda_{u,j}$
$\overline{\mu}_{y,i}$	upper bound of $\mu_{y,i}$
$\overline{\mu}_{u,j}$	upper bound of $\mu_{u,j}$
ΔJ_I	ideal benefit potential
ΔJ_E	existing benefit potential
ΔJ_{MVC}	benefit potential achieved by MVC
ΔJ_D	desired benefit potential to be achieved
R_C	target benefit potential ratio in constraint tuning
R_V	target benefit potential ratio in variability tuning
η_E	existing economic performance index considering disturbances
η_T	theoretical economic performance index with MVC

requirements (Muske, 2003). It is known that the benefit potential comes when the operating point is moved closer to the limit of constraints. Very recently, Xu, Huang, and Akande (2007) studied an MPC performance assessment method with considerations of economic benefit and input and output constraint limits using the back-off approach (Figueroa, Bahri, Bandoni, & Romagnoli, 1996; Lear, Barton, & Perkins, 1995; Loeblein & Perkins, 1998, 1999; Seferlis & Grievink, 2001). The MPC economic performance is evaluated by solving linear and quadratic benefit potential problems in Xu et al. (2007). Xu et al. also suggests tuning guidelines for MPC applications via reducing the variability of controlled variables (CVs) or relaxing the constraint limit of CVs and MVs. The applicability of the method has been demonstrated via simulation examples and pilot-scale experiments. It is noted that, unlike reducing the variability of process variables (PVs), adjusting the constraint limits of MPC applications is a simpler tuning method for MPC applications for improving the economic benefit, which can be done without any dynamic controller tuning effort. In this case, the desired benefit potential can be achievable by simply changing the plant operating point with new constraint limits adjusted according to the MPC economic assessment method. The suggestion in Xu et al. (2007) will be useful to industrial processes. However, for the large size of industrial processes, that is, systems with a large number of CVs and MVs, the performance tuning method in Xu et al. (2007) will not be selective in finding PVs of priority. In most cases, the tuning method in Xu et al. (2007) suggests changing many of CVs and MVs to improve economic profit. In industry, process systems are of large size and all variables are not necessary to change. In practice, it is noted that field process and control engineers have made great efforts to minimize risk, which may result from the controller or the plant operation changes. Also, there are cases where some of the constraint limits are not allowed to change simultaneously.

It is clear that a more practical and selective method is required in the economic performance assessment and tuning of industrial constrained MPC applications. This paper approaches this MPC constraint and variability tuning problem via sensitivity analysis. That is, it is interested in finding the most sensitive or profitable PVs that contribute to the economic profit. Although Xu et al. (2007) mentioned a heuristic method to find sensitive PVs, it has a limited use and in worst-case, it needs to search the whole variable domain to find sensitive PVs. In this paper, a convex optimization based sensitivity analysis method is developed for the economic performance assessment and tuning of MPC applications as an extension of the method in Xu et al. (2007). New optimization algorithms for sensitivity analysis are presented for both selective constraint and variability tuning of industrial MPC applications. The significant objective of sensitivity analysis should be to provide a quantitative suggestion when some tuning guidelines need to achieve a given desired benefit potential. That is, this paper is interested in providing a suggestion for the questions: Which CV/MV is sensitive or profitable for economic performance? How much does it need to be tuned or changed to achieve a given desired benefit potential? In addition, via the proposed sensitivity analysis, this paper represent an attempt to shed light on several new aspects related to sensitivity properties of PVs, i.e., coupled sensitivity and varying sensitivity, which actually arise in the MPC economic benefit analysis. The sensitivity properties and some difficulties in sensitivity analysis will be discussed in detail in the present paper. The proposed economic optimization problem for sensitivity analysis leads to a convex quadratic programming (QP) problem,