Control Engineering Practice 55 (2016) 1–12

Contents lists available at ScienceDirect

Control Engineering Practice

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

Robust tuning for machine-directional predictive control of MIMO paper-making processes ☆

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ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form
14 June 2016
Accepted 15 June 2016
Available online 1 July 2016

Keywords:
MIMO systems
Model predictive control
Controller tuning
Time-domain specifications
Parametric uncertainty
Paper machines

ABSTRACT

This paper solves the controller tuning problem of machine-directional predictive control for multiple-input–multiple-output (MIMO) paper-making processes represented as superposition of first-order-plus-dead-time (FOPDT) components with uncertain model parameters. A user-friendly multi-variable tuning problem is formulated based on user-specified time domain specifications and then simplified based on the structure of the closed-loop system. Based on the simplified tuning problem and a proposed performance evaluation technique, a fast multi-variable tuning technique is developed by ignoring the constraints of the MPC. In addition, a technique to predict the computation time of the tuning algorithm is proposed. The efficiency of the proposed method is verified through Honeywell real time simulator platform with a MIMO paper-making process obtained from real data from an industrial site.

1. Introduction

In paper making with modern high-speed paper machines, sheet properties must be continuously monitored and controlled to guarantee that the paper product quality specifications are satisfied along both the Machine Direction (MD) and Cross Direction (CD) (Chu, Forbes, Backström, Gheorghe, & Chu, 2011; Yousefi et al., 2015). Machine direction indicates the direction towards which the paper moves on the machine, and cross direction is the direction perpendicular to machine direction (Chu et al., 2011). Correspondingly, the MD control accounts for minimizing the variation of several physical properties of the paper product (e.g., dry weight and moisture) with a number of manipulated variables (e.g., stock flow, steam pressure and machine speed) in machine direction. The CD control solves a similar problem but with respect to the paper product qualities along cross direction. In this work, we focus on the tuning problem of the MD Model Predictive Control (MPC) of MIMO plants under parametric uncertainty and consider the time-domain performance indices.

As an important factor in MPC design, the parameter tuning problem is difficult to deal with, especially when MIMO plants and model mismatch are considered simultaneously (Qin & Badgwell, 2003). In the existing literature, the generally utilized idea accounts to investigate the closed-loop performance with respect to each specific controller parameter based on the following two-step analysis: (1) hold all the parameters that affect the controller performance except one to make the tuning problem into a problem with one degree of freedom; (2) adjust this parameter to investigate the relationship between it and the closed-loop system behavior. Based on this type of investigation, some principles for multi-variable MPC tuning were developed, see Fan, Stewart, and Dumont (2003), Garriga and Soroush (2008), also Mohtadi, Shah, and Fisher (1992) and Rowe and Maciejowski (2000). Besides, in Shah and Engell (2011), the authors proposed a systematic approach to adjust the MPC parameters by matching the closed-loop transfer function obtained via the unconstrained MPC with a desired transfer function. In Di Cairano and Bemporad (2010), a systematic tuning method was developed, in which the controller parameters were tuned by minimizing the difference between the MIMO MPC controller and a pre-assigned multi-variable controller, and thus the features of the pre-assigned controller could be inherited. In Kong, Goodwin, and Seron (2013), a metamorphic MPC framework was developed, in which a tuning parameter was incorporated such that one can move smoothly from an existing controller to a new MPC strategy. In addition, the readers can refer to Garriga and Soroush (2010) for a comprehensive review of the

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☆ This work is supported by an NSERC CRD project with Honeywell Vancouver as the industrial partner. A portion of the results presented in this work was submitted as a provisional U.S. patent (He, Shi, Forbes, Backström, & Chen, 2015a).

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http://dx.doi.org/10.1016/j.conengprac.2016.06.008
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existing results on MPC tuning. Based on the above discussions, a user-friendly tuning technique for the uncertain MIMO plants used in the MD-MPC is still missing in the literature. Note that here by user-friendly, we mean the ability of the tuning algorithm to utilize the time-domain performance specifications (e.g., overshoot) and to deal with the parametric uncertainty, both of which are easy to understand and specify compared with the performance indices and uncertainty level defined in the frequency domain (e.g., based on the H_2/H_∞ norm) for the site engineers and operators who may not have the background in robust control theory. Also, a user-friendly tuning algorithm should have an acceptable tuning time.

The starting point of this work is the two-degrees-of-freedom (2-DOF) MPC tuning structure proposed in Chu, Forbes, and Backström (2013). In this framework, two filters F_r and F_d with dynamics adjusted by λ and λ_d, are added to the closed-loop system, and then we can tune the performance of the MPC controller by adjusting λ and λ_d with the original tuning weights fixed to simplify the tuning procedure. For this framework, MD-MPC tuning problems for the single-input–single-output case have been considered and solved in Shi, Wang, Forbes, Backström, and Chen (2015b) and He et al. (2015b). As the MD processes are normally MIMO plants, an easy-to-use MIMO MD-MPC tuner is also of high demand. Thus, based on the 2-DOF MPC structure, we tune the λ and λ_d (which we refer to as λ-parameters hereafter, and are vectors with appropriate dimensions) for the desired robust performance of the closed-loop system, with the original penalty weights in the MPC cost function fixed to pre-assigned values. Based on the industrial experience, the nominal model of the real MIMO plant is available and rather than unstructured uncertainty, which is typically used to date but difficult to understand for end users, parametric uncertainties are considered in this work. The tuning objectives are specified via the overshoot, total variation and settling time for each output of the MIMO system; this enhances the easy-to-use feature of the designed MIMO MD-MPC tuner, yet complicates the problem at hand. As dead time and model mismatch are unavoidable in process operation and model identification, the output responses of the closed-loop system cannot be expressed in an explicit way, and therefore the tuning problem is difficult to formulate. On the other hand, the complexity of the MIMO MD-MPC tuning problem increases with the system size, and how a specific pair of the λ-parameters (e.g., λ_i and $\lambda_{d,i}$ in vectors λ and λ_d) affects the closed-loop responses of all the outputs of the MIMO system is unclear because of the multivariable system structure. Besides, to further improve the easy-to-use feature of the proposed tuning algorithm, the overall time consumption of the MIMO MD-MPC tuning algorithm is not only limited by a pre-specified amount of time, but also required to be predictable without running the algorithm. In regard to the aforementioned challenges, we propose a multi-counter line based algorithm for the MIMO MD-MPC robust tuning problem. The contributions of the work are as following:

1. In order to characterize the extreme step responses of each output for a set of MIMO systems described by parametric uncertainties and to calculate the worst-case time-domain measures, a fast robust performance evaluation technique is developed.
2. A user-friendly MIMO MD-MPC tuning problem is constructed, and then transformed into a number of individual MISO tuning problems, based on which the tuning problem is simplified. Based on the robust performance evaluation method and the simplified tuning problem, a fast multi-variable tuning method is developed for the MIMO MD-MPC, based on which the controller parameters can be tuned for satisfactory performance within acceptable computation time.
3. An efficient technique to predict the overall computation time of the proposed MIMO MD-MPC tuning algorithm is proposed, based on which the end users can predict the tuning time without running the algorithm.

2. Preliminaries and problem formulation

In what follows, the two-degrees-of-freedom MIMO MD-MPC framework developed in Chu et al. (2013) is introduced; the user-friendly tuning objective is also proposed in this section.

2.1. Nominal system and uncertainty

In Fig. 1, $G_p \in \mathbb{R}^{m\times n}$ and $G_0 \in \mathbb{R}^{m\times n}$ are the transfer function matrices of the real process and nominal model respectively. The first-order-plus-dead-time (FOPDT) structure is utilized to model the subsystems in G_p and G_0, as it can provide a good approximation of the process (Chu et al., 2011) and is also easy to understand by the operators of paper machines. Therefore the real process G_p can be represented as

$$G_p(s) = \begin{bmatrix} G_p^{11}(s) & \cdots & G_p^{1n}(s) \\ \vdots & \ddots & \vdots \\ G_p^{m1}(s) & \cdots & G_p^{mn}(s) \end{bmatrix}, G_p^{ij}(s) = \frac{k_{ij}}{\tau_{ij}s + 1}e^{-T_{ij}s}, \quad 1 \le i \le m,$$
$$1 \le j \le n, \tag{1}$$

where k_{ij}, τ_{ij} and T_{ij} are the real process gain, time constant and dead time for $G_p{}^{ij}$. The discretized model of $G_p{}^{ij}$ is $G_p^{ij}(z) = k_{ij}\frac{b_{ij}z^{-1}}{1 - a_{ij}z^{-1}}z^{-T_{ij}^d}$, where $a_{ij} = e^{-\Delta T/\tau_{ij}}$, $b_{ij} = 1 - a_{ij}$, ΔT indicates the sampling time, and T_{ij}^d is the discretized time delay. As model mismatch, disturbance and noises exist in practice, $G_p(s)$ cannot be known accurately. Thus, a nominal model $G_0(s)$ is identified as the approximation of $G_p(s)$:

$$G_0(s) = \begin{bmatrix} G_0^{11}(s) & \cdots & G_0^{1n}(s) \\ \vdots & \ddots & \vdots \\ G_0^{m1}(s) & \cdots & G_0^{mn}(s) \end{bmatrix}, G_0^{ij} = \frac{k_{ij}^0}{\tau_{ij}^0 s + 1}e^{-T_{ij}^0 s}, \quad 1 \le i \le m,$$
$$1 \le j \le n, \tag{2}$$

where k_{ij}^0, τ_{ij}^0 and T_{ij}^0 are usually obtained from some commercial control software based on the input/output data of the real plant, and the discretization of model is achieved similarly as that of the process model. However, the difference between the real process and nominal model is inevitable so that the uncertainties in the model parameters must be considered (Zhang, Zhuang, & Braatz, 2016). Two different kinds of uncertainties are normally used in the robust control, namely parametric uncertainty and unstructured uncertainty. As the unstructured uncertainty is not familiar to our end users, parametric uncertainty is considered for MD-MPC parameter tuning, which can be denoted in the following form:

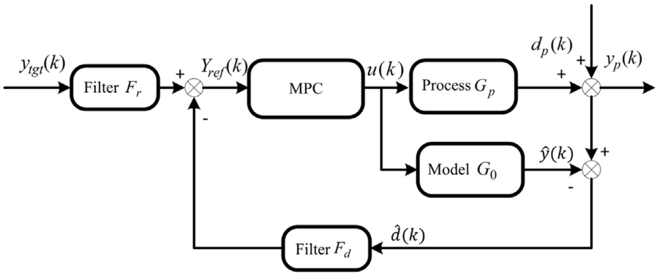

Fig. 1. 2-DOF MPC structure.