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Multiloop robust H_∞ control design based on the dynamic PLS approach to chemical processes

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ABSTRACT

In this paper, a multiloop robust control strategy is proposed based on H_∞ control and a partial least squares (PLS) model (H_∞_PLS) for multivariable chemical processes. It is developed especially for multivariable systems in ill-conditioned plants and non-square systems. The advantage of PLS is to extract the strongest relationship between the input and the output variables in the reduced space of the latent variable model rather than in the original space of the highly dimensional variables. Without conventional decouplers, the dynamic PLS framework automatically decomposes the MIMO process into multiple single-loop systems in the PLS subspace so that the controller design can be simplified. Since plant/model mismatch is almost inevitable in practical applications, to enhance the robustness of this control system, the controllers based on the H_∞ mixed sensitivity problem are designed in the PLS latent subspace. The feasibility and the effectiveness of the proposed approach are illustrated by the simulation results of a distillation column and a mixing tank process. Comparisons between H_∞_PLS control and conventional individual control (either H_∞ control or PLS control only) are also made.

1. Introduction

Multivariable control occurs in nearly all the industrial processes, because the production rate (flow), the inventory (level and pressure), the process environment (temperature), and product quality are normally controlled simultaneously. It is difficult to deal with the control system design because of interactions between input and output variables. Despite the development in multivariable control, decentralized control schemes, also known as multiloop control schemes, are preferred in industrial applications as the multiloop approaches are simple. Moreover, the simplicity of the control structure is easy for control engineers to understand. In each controller only one measured controlled variable is used and only one manipulated variable is adjusted, so the actions of those controllers are relatively easy to monitor. Most importantly, they are tolerant to loop failures. Considerable efforts have been devoted to the development of decentralized control methodologies (Aghdam and Davison, 2007; Akar and Özgüner, 2002; Zhou, 2008). In fact, this does not mean that a single control design can function well for all the unit operations. By virtue of process and loop interactions, it is much more difficult to design and tune multiloop controllers than single loop controllers as the former cannot be done independently. Several methods for the multiloop control design have been proposed, including the detuning method (Xiong et al., 2006),

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the sequential closing method (Loh et al., 1993) and the independent design method (Grosdidier and Morari, 1986). Ideally a given input variable would affect only its own output variable. Unfortunately, the coupling exits in multivariable control loops. To achieve acceptable performance and closed-loop stability of the multiloop system, the manipulated variables and controlled variables are paired to minimize the adverse effects of loop interactions. The relative gain array technique proposed by Bristol (1966) has been widely used for interaction analysis and control loop pairing in industries. However, its drawbacks come out when the process is ill-conditioned or non-squared (Skogestad and Morari, 1987).

To select pairing of controlled and manipulated variables, the controlled system should be "square." A traditional approach dealing with non-square processes is to "square" the system by removing or adding appropriate manipulated variables or output variables. Then common control can be applied to the square system. However, adding an unnecessary variable can increase the control cost while deleting a variable leads to poor performance. In recent literature on control of non-square systems, the Moore–Penrose pseudo inverse of model transfer functions was employed, and the internal model control (IMC) method was used to design Smith delay compensation decoupling controller (Chen et al., 2011). By applying the IMC method, the controllers with equivalent models based on effective open-loop transfer function were designed (Jin et al., 2013). Then, centralized PI/PID controllers with RHP zeros were obtained in (Sarma and Chidambaram, 2005), but the Moore–Penrose pseudo inverse of models may introduce right half plane poles, which would degrade the control performance.

In the past, multivariable statistical techniques, such as principal component analysis and partial least squares (PLS), have been applied to solve process engineering problems of system modeling, monitoring and diagnosis (Gao et al., 2015; Zhang and Hu, 2011). They can condense the variance of the process into a very low-dimensional latent subspace. PLS framework provides a way to decompose the multi-input–multi-output (MIMO) system into several single-input–single-output (SISO) subsystems in the latent space. Kaspar and Ray (1992) first demonstrated the PLS control framework, in which the PLS latent variables were directly utilized in the controller design by employing the PLS matrices as precompensators and postcompensators to bridge the PLS latent space and the original physical space. The advantage of the PLS control structure is that the interaction among loops can be decoupled to a certain extent by decomposing the MIMO process into several independent SISO systems in the PLS latent spaces and loop pairings are avoided. This is practically good for some variables which cannot be paired because of ill-conditioned and non-square processes. Several researchers extended this PLS control design framework to some advanced control strategies. Patwardhan et al. (1998) proposed a constrained nonlinear model-predictive control design method based on Hammerstein and Wiener models in PLS latent spaces. Multiloop adaptive PID controllers were designed based on PLS decomposition structure for linear (Chen et al., 2005) and nonlinear processes (Chen and Cheng, 2004). Hu et al. (2012) presented a multiloop nonlinear IMC scheme based on dynamic nonlinear PLS models by incorporating the ARX model into the neutral network. To deal with the nonlinear dynamic problem, Chi et al. (2013) proposed to combine the PLS framework and the fuzzy model method together. Generalized predictive control controllers were designed under the dynamic PLS framework using a model predictive control relevant identification (MRI) approach (Chi et al., 2014). The control performances of the above methods achieved satisfactory results, because the latent variable models captured the essential information of the correlated data and provided causality in the latent variable space without incomplete decomposition of the controlled variables. However, as the effects of uncertainty may appear in different forms as disturbances or other imperfections in the models used in real industrial systems, a robust PLS control method should be developed to match the practical control system.

Major advances in robust design were made. Robust control is able to deal with the problems of plant/model mismatch (Georgiou and Smith, 1990; Vinnicombe, 1993). Effective robust design methods have been developed, but it is still difficult to directly implement them to the control system because the conventional feedback control structure is different from most the structures of the robust design methods. They were reestablished to link classical control. Advanced robust control and computational algorithms have been made and applied to complex control design problems. To take the effect of system uncertainty into account, design and applications of robust control methods for industrial systems have been considered in literature (Mohanty et al., 2014; Martins et al., 2014; Galán et al., 2000; Howlader et al., 2014). However, the common robust algorithms, such as H_∞ mixed sensitivity algorithm, μ analysis algorithm and loop shaping algorithm, are complex and solving the control problem requires more computing time when the controlled plant is a large scale MIMO system. Furthermore, when the plant is ill-conditioned, it is difficult to access stability robustness. The structured singular value provides a rigorous framework for analyzing and understanding uncertain linear systems (Skogestad et al., 1988). However, as there are always a number of engineering issues which cannot be easily brought into a formal design procedure, one rarely implements the designs. As mentioned before, for practical implementation on the large scale industrial processes, multiloop control is used instead of multivariable robust control as the simplicity of the control structure is easy to understand by plant operators. In this paper, a multiloop robust H_∞ control strategy with the PLS structure is proposed. With the merits of decoupling the MIMO system into several SISO subsystems in the dynamic PLS framework, the robust H_∞ controller in each single control loop can be designed, respectively. This methodology is particularly good for controlling MIMO chemical industrial processes with ill-conditioned and non-square systems.

The remaining paper is organized as follows. In Section 2, the conventional MIMO control problem is defined. The ill-condition and non-square problem is discussed and the PLS based robust control scheme is proposed. A brief review of the PLS compensation method and the PLS based control framework is addressed in Section 3. Section 4 provides the multiloop robust H_∞ control scheme under the PLS framework. In Section 5, a distillation column and a mixing tank process are used to demonstrate the effectiveness of the proposed control strategy for ill-conditioned and non-square multivariable systems. Finally, concluding remarks are made.

2. Revisit of conventional MIMO control

With M controlled and N manipulated variables, a MIMO process whose number of inputs and outputs may be unequal is given as