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Multi-loop design of multi-scale controllers for multivariable processes

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ABSTRACT

Based on the recently proposed (SISO) multi-scale control scheme, a new approach is introduced to design multi-loop controllers for multivariable processes. The basic feature of the multi-scale control scheme is to decompose a given plant into a sum of basic modes. To achieve good nominal control performance and performance robustness, a set of sub-controllers are designed based on the plant modes in such a way that they are mutually enhanced with each other so as to optimize the overall control objective. It is shown that the designed multi-scale controller is equivalent to a conventional PID controller augmented with a filter. The multi-scale control scheme offers a systematic approach to designing multi-loop PID controllers augmented with filters. Numerical studies show that the proposed multi-loop multi-scale controllers provide improved nominal performance and performance robustness over some well-established multi-loop PID controller schemes.

1. Introduction

Most industrial processes are multivariable or multi-input and multi-output (MIMO) in natures where for many decades, the decentralized control architecture (multi-loop PID control) has been widely applied to these types of processes. The main reason that the multi-loop PID control has been preferred to full multivariable control is due to the fact that the multi-loop PID control system is relatively simple to design and implement [1]. However, the effectiveness of the multi-loop PID control in MIMO processes has often been limited by the presence of process interactions or control-loop interactions. The presence of process interactions in MIMO processes has been recognized as one of the main culprits responsible for poor multi-loop control performance. Besides the process interactions, the presences of deadtime (time delay) and inverse-response behaviors have also been recognized as important factors imposing limitation on control performance in process plants. For MIMO processes, a number of multi-loop PID control designs have been proposed over the last decades with the aim to achieve good control performance despite the limitation imposed by process interactions. One example is the independent design method proposed in [2]. This method is quite simple to apply but it has a disadvantage resulting from the negligence of how the other control-loops are designed. This negligence leads to poor control performance. Another example is the sequential design method proposed in [3]. Unlike the independent method, the sequential design method attempts to include the effect of closing subsequent loops into the design problem. Nevertheless, as the control performance can be highly dependent on how the design sequence is chosen, the sequential design method could also result in poor overall control performance [4].

Besides the independent and sequential design methods, another well-known multi-loop control design is based on the detuning approach. In the detuning approach, the performance of individual controllers is first tuned based on a single-loop controller design approach (e.g., Ziegler–Nichols tuning). The individual controllers are then detuned (reduced performance) once all the control loops are closed. A well-known detuning method is the biggest log-modulus (BLT) tuning proposed in [5]. The BLT method is based on the Ziegler–Nichols tuning for each single-loop controller where a single detuning parameter is introduced to meet the stability criterion of the biggest log-modulus. The BLT method is simple to use but it can lead to sluggish or oscillatory responses. In addition to the BLT method, Lee and Edgar [4] proposed another method via which the dominant poles can be shifted to some favorable locations. By shifting the poles to desirable locations, the multi-loop control performance can be improved and sluggish or responses can also be avoided. Another pole placement approach is the root trajectory method proposed by Zhang et al. [6].

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It is interesting to note that some researchers have also proposed the application of Internal Model Control (IMC) to the multi-loop PID control design, i.e., IMC-PID design [7–9]. In the IMC-PID design of Vu et al. [9], the individual PID controller parameters are expressed in term of a single tuning parameter, i.e., based on the closed-loop time constant of each loop. Note that, the controllers designed based on the IMC approach may not be in the first place the same as PID controllers. Hence, in order to obtain the standard PID controllers via the IMC design, a controller reduction process is often required, e.g., in [9] the IMC-based controllers are reduced to PID controllers using Maclaurin series.

Chen and Seborg [10] proposed a method combining the idea of independent design and Nyquist stability analysis. This method consists of two steps: (1) identifying the stability region for PI controllers, and (2) selecting appropriate PI controller settings within this stability region. Advantageously, this method can guarantee the closed-loop stability. Lee et al. [11] proposed a method that combined the Nyquist array analysis with an iterative continuous cycling approach in order to design multi-loop PI controllers. Kaspar and Ray [27] proposed the application of chemometric approach, i.e., principal component analysis (PCA) and partial least squares (PLS) to the design of multi-loop PI control. The advantages of the approach as part of the overall control system design include automatic decoupling and efficient loop paring, as well as the natural ability to handle non-square system. Lakshminarayanan et al. [28] further extended the chemometric approach to the dynamic PLS case, where the reduced process model can be used to design multi-loop control system including feedforward controller. There are many other methods for multi-loop control designs; e.g., see [12–18].

In this paper, we introduce a new multi-loop controller design based on the recently proposed multi-scale control (MSC) scheme for SISO processes proposed by Nandong and Zang [19,20]. The basic principle of the MSC scheme is to decompose a given plant into a sum of few basic modes or factors each with distinct speed of responses – different time-scales. To achieve good nominal control performance and performance robustness it is vital that the required controller is designed in such a way that it can promote good cooperation among these different plant modes. It is interesting to point out that, the designed MSC controller is actually equivalent to a conventional PID controller augmented with a simple (often a first or second order) filter. In this respect, the MSC scheme provides a competitive alternative to PID controller design. We shall demonstrate the applicability and effectiveness of the MSC scheme to designing multi-loop PID control for multivariable processes.

The rest of this paper is organized as follows. In Section 2, a brief overview of the multi-scale control (MSC) scheme and the derivation of two PID controller tuning formulas are presented. In Section 3, a general procedure for the multi-loop MSC controller design and a simple algorithm based on the MSC-PID tuning formulas are provided. Section 4 presents some illustrative examples to compare the performances of the proposed multi-loop MSC controllers (equivalent PID controllers) with some of the existing multi-loop PID controller designs including the centralized model predictive control (MPC) strategy. Finally, some concluding remarks and future work are highlighted in Section 5.

2. Fundamental of multi-scale control scheme

2.1. Preliminary

In the multi-scale control (MSC) scheme proposed by Nandong and Zang [19,20], it is assumed that a given plant of interest can be decomposed (via partial fraction expansion) into a sum of basic modes or factors. These basic modes should be different in their speed of responses to a given input (manipulated variable)–the modes with multi-scale dynamics.

In general, for a single-input single-output (SISO) process the decomposition in the MSC scheme can be represented as

$$P(s) = M_0(s) + M_1(s) + M_2(s) + \cdots + M_n(s) \tag{1}$$

where $P(s)$ denotes the plant and $M_i(s)$, $\forall i \in \{0, 1, 2, \ldots, n\}$ represent the plant modes, which could be either a first or second order transfer function with real coefficients. It is also assumed that $M_j(s)$ has a slower speed of response than $M_{j+1}(s)$, $\forall j \in \{0, 1, \ldots, n-1\}$. Note that, Eq. (1) implies that the plant P can be decomposed into a sum of $n+1$ basic modes.

The principle of the MSC scheme is to synthesize a controller that can enhance cooperation among the different plant modes, which is crucial to improve both nominal performance and performance robustness. To achieve this enhanced cooperation, the MSC scheme advocates the idea of using several individual sub-controllers where each sub-controller is tailored to control a specific plant mode. In theory, for a given plant that can be decomposed into a sum of $n+1$ basic modes, there will be $n+1$ number of separate sub-controllers required. In a practical application, however, a fewer number of sub-controllers might in fact be required than in the ideal case where this can be done by applying a model reduction process to a given high-order process based on which the controller is designed. For example, a fourth-order process model will ideally require four sub-controllers. If the fourth-order model could be reduced to a second-order model, then the MSC scheme based on this reduced model will only require two sub-controllers.

2.2. Realization of the multi-scale control scheme

The details about the MSC scheme can be found in the recent papers by Nandong and Zang [19,20]. Here, we only present a brief overview of the scheme based on the 3-layer MSC structure. Fig. 1 shows the realization block diagram of the 3-layer MSC structure. It is assumed that a given plant $P(s)$ can be decomposed into a sum of three basic modes. Referring to Fig. 1, K_i is the sub-controller to control the mode $M_i(s)$, $\forall i \in \{0, 1, 2\}$; $W_j(s)$, $j = 1, 2$ the multi-scale predictor for the jth-inner-loop; E, D, R, Y and U_i denote the signals for error, disturbance, setpoint, controlled variable and ith-sub-controller output, respectively. Notice that, the 3-layer MSC scheme shown in Fig. 1 can be reduced to a single-loop block diagram as shown in Fig. 2.

The multi-scale predictor $W_j(s)$, $j = 1, 2$ is often chosen to be the inner mode

$$\mathbf{W}(s) = \begin{bmatrix} W_1(s) \\ W_2(s) \end{bmatrix} = \begin{bmatrix} \bar{M}_1(s) \\ \bar{M}_2(s) \end{bmatrix} \tag{2}$$

where $\bar{M}_i(s)$ denotes the nominal model for the mode $M_i(s)$.

Referring to Fig. 2, the innermost layer ($n = 2$) transfer function is written as follows

$$G_2(s) = \frac{U_2(s)}{U_1(s)} = \frac{K_2(s)}{1 + K_2(s)W_2(s)} \tag{3}$$

where the next inner-layer ($n = 1$) transfer function can be expressed as

$$G_1(s) = \frac{K_1(s)}{1 + K_1(s)W_1(s)G_2(s)} \tag{4}$$

The overall multi-scale controller K_{msc} can be obtained as follows

$$K_{msc}(s) = K_0(s)G_1(s)G_2(s) \tag{5}$$