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New results on VRFT design of PID controller

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ABSTRACT

Virtual reference feedback tuning (VRFT) design method can be applied to determine the parameters of a PID controller from the available process input and output data without resorting to the identification of a process model. Although it is an attractive alternative to the popular model-based controller design methods, the existing results are restricted to the linear systems. In this paper, an adaptive VRFT design method with application to the adaptive PID controller design is proposed. In addition, the relationship between the VRFT and IMC designs is analyzed as well. Simulation results are presented to illustrate the advantage of the adaptive VRFT design over the conventional VRFT design.

1. Introduction

Model-based techniques have been the predominant controller design methods that have received much research interest in the past several decades. For example, based on the transfer function models like first-order-plus-dead-time model, various PID tuning formulas including ITAE performance index, direct synthesis design method (Seborg et al., 1989), and Internal Model Control (IMC) design (Morari and Zafiriou, 1989) are well established in the literature. Generally, model-based controller design methods involve a two-step procedure, where the first step is to identify a process model among the pre-specified model structures that gives reasonably good modeling accuracy, followed by the controller design based on the model thus obtained. However, these model-based design methods suffer the following drawbacks. First, those simplified transfer function models employed in controller design may not carry sufficient information for the process under control and thus the performance of the resulting controller will become poor if the discrepancy between the process and model is too large. Even when those models have acceptable modeling accuracy, a trial and error procedure is normally required to evaluate which model is best suited for controller design to give the best control performance.

An alternative is to develop controller design methods to obtain the parameters of feedback controller from the available process input and output data without the need of model identification. To this end, (Hjalmarsson et al., 1994, 1998) developed the iterative feedback tuning (IFT) method with promising result for real applications. However, the IFT may require considerable computational time to obtain a solution with a risk of being a local optimum in the proposed minimization problem, not to mention its dependence on the trial and error procedure for initialization. Furthermore, its computation needs unbiased estimates of some variables, which impose much more stringent requirements on the experiment. As a result, the experiment required for the IFT is typically complicated. Spall and Cristion (1998) proposed a stochastic approach for adaptive control using a function approximator (FA) to calculate the action needed from the controller. FA can be a polynomial or an artificial neural network, whose parameters are updated repeatedly in accordance with the minimization of a cost function. However, since a plant model is not available, the gradient of this cost function has to be evaluated by simultaneous perturbation stochastic approximation instead of quadratic methods. Thus, the computational burden of this method is very high due to the iterations and the convergence of the trained parameters may not be guaranteed.

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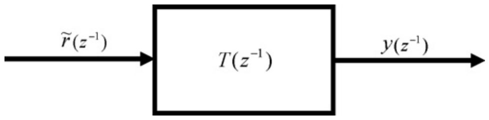

Fig. 1 – Reference model.

To alleviate the aforementioned drawbacks, Campi et al. (2000, 2002) proposed the virtual reference feedback tuning method (VRFT) which stems from the idea of virtual input direct design (VID^2) (Guardabassi and Savaresi, 1997; Savaresi and Guardabassi, 1998), but in a better organized form. Under this tuning framework, only the specification of desired reference model is required. Nakamoto (2005) extended this controller design technique to multivariable chemical process application. However, this design framework is originally developed for linear systems and thus its application to nonlinear systems is restricted.

In this paper, the relationship between the VRFT and IMC designs is firstly analyzed. Next, an adaptive VRFT design method with application to the adaptive PID controller design is developed. In the proposed adaptive VRFT design, the off-line database employed in the conventional VRFT design is continuously updated by adding the current process data into the database. Furthermore, PID parameters are determined by the VRFT design at each sampling instant using the relevant dataset selected from the current database based on the nearest neighborhood criterion. Simulation results are presented to illustrate the proposed design and a comparison with the conventional VRFT design is made.

2. The VRFT design framework

The VRFT method approximately solves a model-reference problem in discrete time as depicted in Fig. 1, where the reference model $T(z^{-1})$ describes the desired behavior of the closed-loop system consisting of a linear time-invariant process $P(z^{-1})$ and a parameterized controller $C(z^{-1};\theta)$ as shown in Fig. 2. Let us assume that $P(z^{-1})$ is unknown and only a set of process input and output data, $\{u(k)\}_{k=1\sim N}$ and $\{y(k)\}_{k=1\sim N}$, have been collected from the experiment on the plant and that a reference model $T(z^{-1})$ has been chosen. The design goal is to solve θ, a vector consisting of the controller parameters, such that the feedback control system in Fig. 2 behaves as closely as possible to the pre-specified reference model $T(z^{-1})$.

Given the measured output signal $\{y(k)\}_{k=1\sim N}$, the corresponding reference signal $\{\tilde{r}(k)\}_{k=1\sim N}$ in Fig. 1 is obtained by

$$\tilde{r}(z^{-1}) = T^{-1}(z^{-1})y(z^{-1}) \tag{1}$$

where $\tilde{r}(z^{-1})$ and $y(z^{-1})$ are the Z-transforms of discrete-time signals $\{\tilde{r}(k)\}_{k=1\sim N}$ and $\{y(k)\}_{k=1\sim N}$, respectively. $\tilde{r}(z^{-1})$ is called 'virtual' reference signal because it does not exist in reality and in fact it was not used in the generation of $y(k)$. However, it plays a pivotal role in the VRFT framework in that the fundamental idea of the VRFT framework is to treat $\{y(k)\}_{k=1\sim N}$ as the desired output of the feedback system when the reference signal is specified by $\{\tilde{r}(k)\}_{k=1\sim N}$. As a consequence, given error signal $e(k) = \tilde{r}(k) - y(k)$, the controller output $\tilde{u}(k)$ is calculated as:

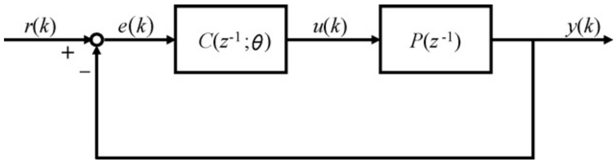

Fig. 2 – Feedback control system.

$$\tilde{u}(z^{-1}) = C(z^{-1};\theta)\{\tilde{r}(z^{-1}) - y(z^{-1})\} \tag{2}$$

where $\tilde{u}(z^{-1})$ is the Z-transforms of discrete-time signal $\{\tilde{u}(k)\}_{k=1\sim N}$.

It is noted that, even though the process dynamics $P(z^{-1})$ is not known, when the process is fed by $u(k)$, i.e. the measured input signal, it generates $y(k)$, i.e. the corresponding measured output signal. Therefore, a good controller generates $u(k)$ when the error signal is given by $e(k)$. The idea is then to search for $C(z^{-1};\theta)$ whose output $\tilde{u}(k)$ matches $u(k)$ as closely as possible. Hence, the controller design task reduces to the following minimization problem:

$$J(\theta) = \min_{\theta} \frac{1}{N}\sum_{k=1}^{N}\{u(k) - \tilde{u}(k)\}^2 \tag{3}$$

If the controller is given by $C(z^{-1};\theta) = \rho^T(z^{-1})\theta$ where $\rho(z^{-1})$ is a vector of discrete-time transfer function, it can be seen that Eq. (3) is quadratic in θ. Consequently, the controller parameter θ^* which minimizes Eq. (3) can be explicitly obtained by the least-square technique. As a result, the VRFT design framework effectively recasts the problem of designing a model-reference feedback controller into a standard system-identification problem. More detailed discussions on the VRFT are referred to Campi et al. (2000, 2002).

3. PID controllers design by the VRFT method

To illustrate the VRFT design in more detail, its application to PID design is discussed in this section. Consider a PID controller given by:

$$\begin{aligned} u(k) = \; & u(k-1) + K_P\{e(k) - e(k-1)\} \\ & + K_I e(k) + K_D\{e(k) - 2e(k-1) + e(k-2)\} \end{aligned} \tag{4}$$

where $u(k)$ is the manipulated variable at the k-th sampling instant, $e(k)$ is the error between the process output and its set-point at the k-th sampling instant, and K_P, K_I and K_D are the PID parameters.

In VRFT design framework, the reference model $T(z^{-1})$ is specified by the following first-order equation:

$$T(z^{-1}) = \frac{(1-A)z^{-1}}{1-Az^{-1}} \tag{5}$$

where A is a tuning parameter related to the speed of response. To design a PID controller by the VRFT method, the virtual input $\tilde{u}(z^{-1})$ is calculated by Eqs. (1), (2), and (5) to obtain

$$\tilde{u}(z^{-1}) = \left[K_P + \frac{K_I}{1-z^{-1}} + K_D(1-z^{-1})\right]\frac{1-z^{-1}}{(1-A)z^{-1}}y(z^{-1}) \tag{6}$$

Eq. (6) can be rewritten as

$$\tilde{u}(k) = \Psi(k)K \tag{7}$$