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Intelligent virtual reference feedback tuning and its application to heat treatment electric furnace control

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ABSTRACT

Virtual Reference Feedback Tuning (VRFT) is a data-driven one-shot control method which is very attractive for engineering applications. However, it cannot design controllers with the optimal control performance based on the standard VRFT approach as performance indices are not explicitly represented in its objective function. To deal with this problem, this paper presents a novel intelligent VRFT (IVRFT) based on adaptive binary ant system harmony search (ABASHS) where the reference model of VRFT, which potentially determines the control performance, is coordinately optimized with the controller by ABASHS to achieve the best control performance. Finally, the proposed ABASHS-based intelligent virtual reference feedback tuning (ABASHS-IVRFT) method is applied to the temperature control of the heat treatment electric furnace. The simulation results demonstrate that ABASHS-IVRFT is valid and can implement the optimal non-overshoot control easily and efficiently. Considering the characteristics such as ease of implementation and no need of the model information of controlled objects, ABASHS-IVRFT is a promising approach for engineering applications.

1. Introduction

With the development of computer science and engineering technologies, industrial production processes have been becoming more and more complex, and therefore modeling industrial processes using first principles or identification are more challenging, which causes that the traditional model-based control theories and methods are impractical for control issues. On the other side, with the wide applications of control systems such as the Distrusted Control System and Fieldbus Control System, huge amount of process data are stored which contain all the valuable state information of process operations and equipment. With these process data, controllers can be directly designed by data-driven control (DDC) methods without the process models (Hou and Wang, 2013). As DDC methods only need the data from the process, they significantly relieve the effort of modeling the complicated process and equipment. Due to this attractive characteristics, DDC methods have been drawing more and more attention and various DDC methods have been proposed and studied, such as unfalsified control (Helvoort et al., 2008; Van Helvoort, 2007; Van Helvoort et al., 2007), iterative feedback tuning (Hjalmarsson, 2002; Kissling et al., 2009; Huusom et al., 2009), iterative learning control (Ahn et al., 2007; Chen, 1998; Chi and Hou, 2007; Owens et al., 2014; Rubio, 2014b), model-free adaptive control (Cang et al., 2011; Coelho, 2009), virtual reference feedback tuning (VRFT) (Guardabassi and Savaresi, 2000), and various adaptive control approaches (Blazic et al., 2003; Rubio, 2014a).

VRFT is a one-shot discrete-time controller tuning methodology as the controller design based on VRFT only needs a set of input-and-output data of linear or nonlinear controlled objects (Campi et al., 2002; Campi and Savaresi, 2006). Attracted by the advantage of one-shot and easy implementation, VRFT has been a new hotspot of DDC methods and improved VRFT approaches have been developed to tackle various control problems. Sala and Esparz (2005a) discussed the variant of basic VRFT to alleviate noise-induced correlation in the open-loop case and applied VRFT to unstable plants. Besides, they also introduced a validation step based on the data to check the stability of the obtained controller. Later, they further extended the VRFT approach for non-minimum phase (NMP) system (Sala and Esparza, 2005b). After that, Campestrini et al. (2011) introduced the idea of iterative feedback tuning into VRFT and presented a new two-step method to design the controller of a non-minimum phase system. Through modifying the reference model of VRFT so as to include NMP zeroes in the second step, the problem of unstable pole-zero cancellation was addressed. Nakamoto (2004) first attempted to employ VRFT to design the controllers of Multi-input Multi-output (MIMO) systems. Afterward, Rojas et al. (2012)

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further studied MIMO controller design based the VRFT method where a pre-process step and a decoupling operation were included to subtract the impact of sensor noise and handle the interactions among different control loops, respectively. Kansha et al. (2008) proposed an adaptive VRFT method in which the current process data were incorporated for proportional-integral-derivative (PID) controller design. As the relevant data which is corresponding to the current operating condition are selected based on the nearest neighborhood criterion and used to calculate the parameters of controllers via VRFT, the obtained adaptive PID controller can achieve better performance than that of PID controller design over the conventional VRFT method in nonlinear process control. Nowadays, VRFT has been extended to various controller designs such as PI or PID controllers (Kansha et al., 2008; Passenbrunner, 2014; Yang et al., 2012), the two-degree-of-freedom linear controller (Lecchini et al., 2002), the artificial neural network controller (Esparza et al., 2011; Wang, 2011) and neuroendocrine ultrashort feedback controller (Ding et al., 2015), and the enhanced VRFT approaches successfully solve various control problems such as water treatment plant control (Rojas et al., 2012), internal combustion engine control (Passenbrunner, 2014), solid oxide fuel cell system control (Li et al., 2012), biomedical neuroprotheses control (Previdi et al., 2004), freeway traffic ramp metering system control (Jin et al., 2014), nonlinear Hammerstein and Wiener systems control (Jeng, 2014) and 3D crane control (Radac et al., 2015).

The VRFT methodology formulates the controller tuning problem as a controller parameter identification problem via introducing virtual reference signal with a pre-defined reference model (Previdi et al., 2004), and then the parameters of controllers can be easily calculated by the least square method with the data collected from the controlled loop. However, none of control performance metrics are included in the standard VRFT objective function, and thus it is impractical to design the optimal controllers by tuning controllers with VRFT directly, which makes VRFT less attractive for real engineering applications. Fortunately, the control performance is determined by the reference model, and thus we can achieve the expected control metrics by using an ideal reference model. However, in the previous work VRFT is basically studied as an identification problem, and how to choose the optimal reference model is not concerned in traditional VRFT methods. Moreover, constructing a perfect reference model is a challenging problem of which the detailed analysis will be given in the following section. To solve this problem, a novel intelligent virtual reference feedback tuning (IVRFT) approach is presented in this paper in which the controller and the reference model are tuned simultaneously and consequently the optimal control performance can be realized in the extended IVRFT framework. Compared with other traditional off-line controller design methods based on meta-heuristics (Menhas et al., 2012; Wang et al., 2013a, 2014), the information of the model of controlled objects is not needed in the developed approach thanks to the data-driven characteristic of VRFT. As the least square method cannot optimize the parameters of the reference model and the controller simultaneously, an adaptive binary ant system harmony search (ABASHS) algorithm is developed to solve IVRFT problems.

The reminder of this paper is organized as follows. ABASHS is first introduced in Section 2 for describing IVRFT better. Section 3 introduces the proposed intelligent virtual reference feedback tuning approach in detail. Then in Section 4 the IVRFT based on ABASHS is applied to the heat treatment electric furnace control and the control performance is compared with other methods. Finally, the conclusions are drawn in Section 5.

2. Adaptive binary ant system harmony search

Harmony Search (HS) algorithm is a meta-heuristic algorithm first proposed by Geem et al. (2001), which is inspired by the process of music players searching for a perfect state of harmony. Due to its simplicity, flexibility and effectiveness, HS has drawn increasing attention and been successfully applied to various areas of science and engineering (Manjarres et al., 2013; Kong et al., 2015a and b; Geem, 2005; Wang et al., 2013b; Nazari-Heris and Mohammadi-Ivatloo, 2015).

Usually the parameter values of controllers need not have a high accuracy, thus binary coding has some advantage on controller design problems since the binary-coding strategy discretizes the whole search space as finite candidate solutions which consequently improves the search efficiency (Menhas et al., 2012; Wang et al., 2013a). Considering this potential benefit of binary-coding, we adopt binary HS to solve IVRFT problems in this paper. The standard HS algorithm with binary-coding can be used to solve binary-coded problems directly and achieves better results on the water pump switching problems than the standard Genetic Algorithm (Geem, 2005). However, the dysfunction of the pitch adjustment operator of HS in binary space degrades the performance of HS, and therefore it is essential to study and modify binary-coded HS (Wang et al., 2013b; Nazari-Heris and Mohammadi-Ivatloo, 2015; Ling et al., 2011). Wang et al. (2013b) proposed an improved adaptive binary harmony search (ABHS) algorithm to enhance the search ability and robustness of the algorithm, which was extended to design the optimal fuzzy controller (Wang et al., 2013a) later. Kong et al. (2015a) developed a new simplified binary harmony search algorithm to tackle large scale 0–1 knapsack problems and then presented a new modified binary harmony search (NBHS) algorithm (Kong et al., 2015b) for solving multidimensional knapsack problem. Recently Nazari-Heris and Mohammadi-Ivatloo (2015) designed an upgraded binary harmony search algorithm to solve the optimal placement of phasor measurement units for complete observability of power networks. These works show that binary-coding HS has potentially promising applications in engineering problems.

In our previous work (Ling et al., 2011), we first introduced the idea of Ant System into HS and developed a new binary HS in which the structure of the Harmony Memory (HM) and the search operators, i. e. the harmony memory consideration operator (HMCO) and pitch adjustment operator (PAO), are re-defined to enhance the performance of binary HS. Based on it, this paper presents an adaptive ant system harmony search algorithm which further introduces an adaptive strategy for improving the global and local search ability of the algorithm as well as relieving the effort of setting the algorithm parameters in applications.

2.1. Initializing the Harmony Memory

As ABASHS uses binary-coding, the solution is represented as a binary vector. In the standard binary HS (BHS), a certain number of harmony vectors, i. e. solutions, are initialized randomly as Eq. (1)

$$H=\begin{bmatrix} H_1 \\ H_2 \\ \cdots \\ H_i \\ \cdots \\ H_N \end{bmatrix}=\begin{bmatrix} h_{11}\, h_{12} \dots h_{1j} \;\dots\; h_{1M} \\ h_{21}\, h_{22} \dots h_{2j} \;\dots\; h_{2M} \\ \dots \\ h_{i1}\, h_{i2} \dots\; h_{ij} \dots\; h_{iM} \\ \dots \\ h_{N1}\, h_{N2} \dots h_{Nj} \dots h_{NM} \end{bmatrix} h_{ij} \in \{0,1\},$$
$$i \in \{1, 2, \dots, N\}, \quad j \in \{1, 2, \dots, M\} \tag{1}$$

where N is the number of harmony vectors and M is the dimension of solution. Then, according to the presetting harmony memory size (HMS), the best HMS solutions are chosen from H and stored in the Harmony Memory (HM) for guiding the following search of the algorithm. Different from the standard BHS, ABASHS follows the global and current best information to perform searching, which is inspired by the nature of the search mechanism of Ant System (Wang et al., 2008), and therefore the HM of ABASHS only contains the global best solution and the best individual of the