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Data-driven controller design for general MIMO nonlinear systems via virtual reference feedback tuning and neural networks

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ABSTRACT

In this paper, we develop a novel data-driven multivariate nonlinear controller design method for multi-input–multi-output (MIMO) nonlinear systems via virtual reference feedback tuning (VRFT) and neural networks. To the best of authors' knowledge, it is the first time to introduce VRFT to MIMO nonlinear systems in theory. Unlike the standard VRFT for linear systems, we restate the model reference control problem with time-domain model in the absence of transfer functions and simplify the objective function of VRFT without a linear filter. Then, we prove that the objective function of VRFT reaches the minimum at the same point as the optimization problem of model reference control and give the relationship between the bounds of the two optimization problems of model reference control and VRFT. A three-layer neural network is used to implement the developed method. Finally, two simulations are conducted to verify the validity of our method.

1. Introduction

Traditionally, a suitable controller is designed by the mathematical model of the plant which is identified from the input and output data. However, with the rapid development of science and technology, the industrial process and production equipment become more and more complex, which makes establishing accurate mathematical models costly and even unattainable. Imprecise models will bring about the model error into the controller, which implies that the system cannot reach the expected goal. Fortunately, with the development of information technology, especially the accurate sensor technology and data storage technology, huge amounts of data are recorded and stored in the daily production. To make full use of data and solve the direct control design problem, data-driven control is proposed and gets the attention of more and more researchers.

Compared with model-based control, data-driven control designs the controller directly without mathematical models. Progress has been made to show the advantages of data-driven control over traditional model-based controls [1–3]. In the past few decades, various data-driven methods have been proposed under some system hypotheses in different environments. Tuning the controller online by estimating the gradient of the goal function is an effective idea of the data-driven control. For instance, simultaneous perturbation stochastic approximation (SPSA) introduced by Spall estimates the gradient by stochastic approximation [4,5] and model free adaptive control (MFAC) proposed by Hou replaces the gradient with pseudo-partial derivative [6–8]. The idea of iterations also has good applications in data-driven method. For instance, iterative learning control (ILC) [9–14] suits for the systems when the off-line data can be obtained repeatedly or periodically and iterative feedback tuning (IFT) developed by Hjalmarsson [15–17] is based on an iterative gradient descent approach. Additionally, in the field of optimal control, adaptive dynamic programming (ADP) [18–21] is a significant and hot topic. Many data-driven and model-free methods based on ADP have been established [22–32]. Different from the above methods, virtual reference feedback tuning (VRFT), which is originally proposed by Guardabassi and Savaresi [33], provides a global solution to a model reference control problem with one-shot off-line data. VRFT has the advantages of less calculation than iterative methods, global optimal solution compared to local optimal solutions of gradient methods and just one-shot off-line data with no need of detected signal. Until now, VRFT has been developed for single-input single-output (SISO) linear systems [34,35], multi-input multi-output (MIMO) linear systems [36,37], and SISO nonlinear systems [38,39].

In the aspect of applications, more and more data-driven control methods are designed to solve practical problems in recent years. In [40], a data-driven approach was designed to control

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batch processes with applications to a gravimetric blender. Marcel et al. proposed a robust data-driven control for solving synchronization problem [41]. An iterative data-driven tuning method of controllers was developed for nonlinear systems with applications to angular position control of an aerodynamic system [42]. A data-driven self-tuning control was designed by iterative learning control to optimize the control parameters of turbocharged engines [43]. In [44], Chi et al. presented a unified data-driven design framework of optimality-based generalized iterative learning control. VRFT was also applied to nonlinear systems by neural controllers [45] and MIMO linear systems [46,37].

However, as a well-known data-driven method, there are very few results of VRFT for MIMO nonlinear systems in both theory and applications. Different from SISO nonlinear systems and linear systems, MIMO nonlinear systems are much more complex, and it is a much tougher task to demonstrate the validity of VRFT in this case. Nevertheless, data-driven control aims to solve the control problem of complex and highly nonlinear plant, and the theory of linear systems and SISO systems is not sufficient. Therefore, it is of great importance to investigate VRFT for MIMO nonlinear systems. To the best of our knowledge, our work is the first to present the theoretical analysis of VRFT for MIMO nonlinear systems.

This paper studies the problem of model reference controller design of general MIMO nonlinear systems by using VRFT and proves the validity of the established method. First, to avoid the difficulty of solving nonlinear transfer function, we recall the optimization problem of model reference control with time-domain model. Second, we prove that the time-domain model optimization problems of VRFT and the model reference control have the same solution. We also obtain the relationship of the bounds of the two optimization problems. Finally, we provide the implementation of VRFT in MIMO nonlinear systems by neural networks.

The rest of this paper is organized as follows. Section 2 gives the basic assumptions of the system and presents the optimization problem of model reference control in MIMO nonlinear systems. Section 3 describes the VRFT approach in MIMO nonlinear systems and proves the equivalence of the optimization problems of model reference control and VRFT. Furthermore, the relationship between the bounds of the two problems is also discussed in this section. Section 4 introduces a three-layer neural network to approximate the controller with the aid of VRFT. Section 5 illustrates the simulation results in noiseless and noisy environments which show the effectiveness of our method, respectively. Section 6 gives the conclusion.

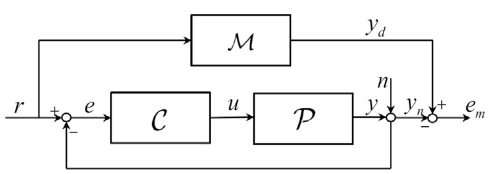

Fig. 1. Model reference control.

2. Optimization problem of model reference control

The control system is shown in Fig. 1. u is the control input and y is the output of the plant. y_n is the plant output corrupted by noise n and r is the reference signal. It is a classical closed-loop control system where the controller $\mathcal{C}$ processes the error signal e so as to generate the control input u to the plant $\mathcal{P}$. The plant $\mathcal{P}$ and the controller $\mathcal{C}$ are nonlinear and multivariate. We assume that there is a reference model $\mathcal{M}$ which describes the relationship between the reference input r and the desired output y_d. Our goal is to design the controller $\mathcal{C}$ to make the performance of the closed-loop control system as close as possible to $\mathcal{M}$, which means that the error e_m between the output of control system and reference model with the same reference input is as small as possible.

For linear systems, the transfer function model is used to describe the problem of model reference control [33,36]. However, it is well known that the transfer function is not suitable for the

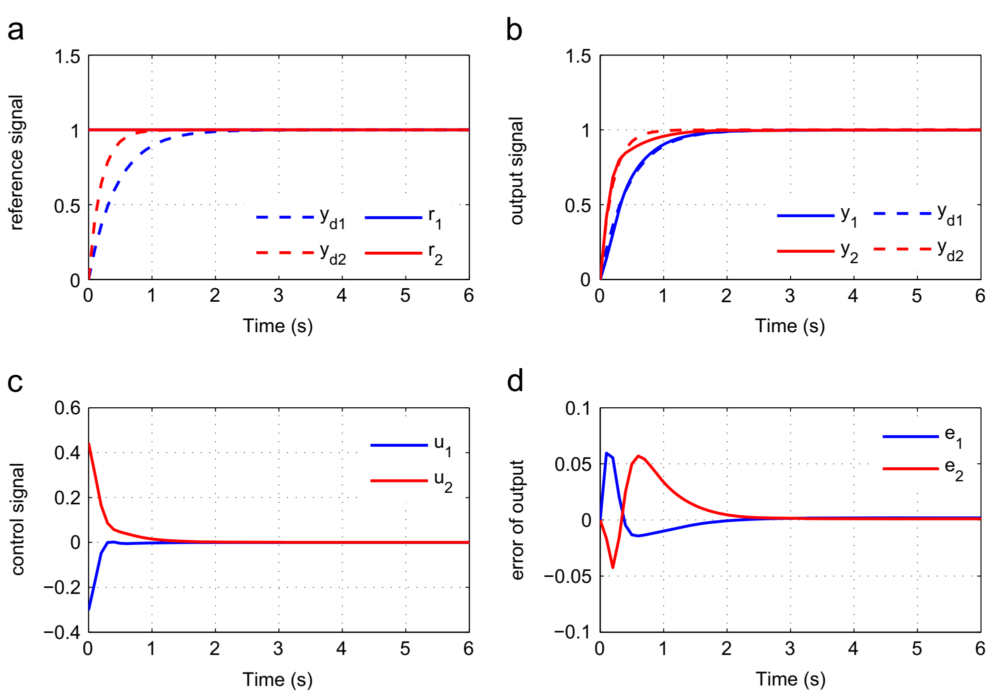

Fig. 2. Responses of the system with reference to unit step signal in noiseless environment. (a) Reference input r and desired output y_d. (b) Desired output y_d and actual output y. (c) Control signal u_1 and u_2. (d) Error of output e_1 and e_2.