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Nonlinear multiobjective model-predictive control scheme for wastewater treatment process☆

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ABSTRACT

A nonlinear multiobjective model-predictive control (NMMPC) scheme, consisting of self-organizing radial basis function (SORBF) neural network prediction and multiobjective gradient optimization, is proposed for wastewater treatment process (WWTP) in this paper. The proposed NMMPC comprises a SORBF neural network identifier and a multiple objectives controller via the multi-gradient method (MGM). The SORBF neural network with concurrent structure and parameter learning is developed as a model identifier for approximating on-line the states of WWTP. Then, this NMMPC optimizes the multiple objectives under different operating functions, where all the objectives are minimized simultaneously. The solution of optimal control is based on the MGM which can shorten the solution time. Moreover, the stability and control performance of the closed-loop control system are well studied. Numerical simulations reveal that the proposed control strategy gives satisfactory tracking and disturbance rejection performance for WWTP. Experimental results show the efficacy of the proposed method.

1. Introduction

Wastewater treatment process (WWTP) is difficult to be controlled because of its biological, physical and chemical phenomena are complex, interrelated and highly nonlinear [1,2]. Moreover, stringent standards and regulations have been recently introduced worldwide to protect the environment from the effect of harmful waste in effluent discharged to receiving waters [3,4]. The operation of WWTP should continuously meet effluent requirements, preferably at the lowest possible energy cost [5,6]. In order to achieve this, control of such plants can be very helpful but, given the complexity, this is not an easy task. Operators are often reluctant to design new control strategies on WWTP because of their possibly unexpected behavior [7,8].

Several authors have discussed the control scheme design and control methods in relation to WWTP control, spanning from classical control methods such as feedback and feedforward control [9–11] to advanced model based and multivariable control [12–14]. The full-scale control scheme has been boosted by the online sensor technology and the introduction of control methods [15]. The major goals of the controllers are to keep the plant running, satisfy the effluent requirements, minimize operating costs, etc. [16,17]. Recently, model predictive control (MPC), employs a prediction model of the plant to optimize future plant behavior, has been a popular approach for WWTP [18–20]. Holenda et al. proposed a MPC method for determining DO concentration [21]. However, their work was focused on DO control rather than multivariable control. To keep the quality of the effluent within regulated limits, Shen et al. implemented the MPC strategy with the Benchmark Simulation Model 1 (BSM1) for WWTPs [22]. Acceptable performance is obtained by combining the feedforward controllers and taking into consideration the influent ammonium concentration and the flow rate. But, in some cases in which the influent ammonium concentration is not measured, its estimation requires an observer. O'Brien et al. investigated a case study application of MPC in which the technique was used in a WWTP in Lancaster [23]. The MPC system provided significant benefits, including a reduction of more than 25% in power usage and a similar increase in plant efficiency. There are other MPC approaches to controlling DO concentration [24,25]. However, for the former MPC controllers [21–25], the closed loop behaviors of WWTP differ with respect to their objectives and methods. These MPC controllers pay attention to individual variables and feature the system by a single objective function. Since the organic matter removal process are interconnected, it would

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be reasonable to consider the WWTP as a multiobjective problem from a process control point of view [26].

In fact, WWTPs are the control problems with several objectives to be optimized simultaneously. Based on the modifications of the BSM1, Cadet et al. used a simple *L*/*A* control law for WWTPs [27]. The switch has been realized by fuzzy logic. The results are as expected with an improvement of nitrogen removal. In this case the cost will be increased and the control actions will behave relatively roughly. Stare et al. introduced several control strategies for nitrogen removal are proposed and evaluated in a benchmark simulation model of an activated sludge process [28]. Results of the simulation show that with PI and feedforward controllers almost the same operating costs can be achieved as with MPC strategies under various plant operating conditions. MPC strategies are advantageous only in cases where the plant is highly loaded and if stringent effluent fines are imposed by legislation. To fulfill the effluent quality standards, while minimizing the operational costs, a quadratic dynamic matrix control (QDMC) method to control the influent flow rate and ammonium concentration have been investigated by Shen et al. [29]. The simulation results indicate that good performance of QDMC. Rojas et al. applied the virtual reference feedback tuning (VRFT) to multiple-input multiple-output (MIMO) control strategies in WWTPs [30]. Using BSM1 as a case study, the proposed VRFT approach provides reduced-order controllers only using a batch of input–output data points, obtained from an open-loop experiment. The results show that substantial improvements in the plant performance can be obtained when controllers are implemented. However, the former controllers [27–30] weight the individual objectives so that a single objective function is formed by combining the individual objectives. This way of approaching the multiobjective problem for WWTP is not the best manner of solving such problems because assigned weights are subjective. Moreover, a major requirement for achieving these controllers [18–25,27–30] relies on real-time supervision of important process indicators related to effluent quality and plant performance. And an analysis of the operational data indicated that the on-line hardware sensors frequently provided incorrect process measurements [31–33].

In order to obtain a suitable multivariable control strategy for WWTP with some software sensors, a nonlinear multiobjective MPC (NMMPC) is proposed in this paper. The proposed NMMPC comprises a self-organizing radial basis function (SORBF) neural network identifier and a multiple objectives controller with the multiobjective gradient optimization method. This NMMPC has its simplicity in parallelism to MPC design and efficiency to deal with computational complexity. The contributions of this paper are as follows.

First, a SORBF neural network identifier is developed in this paper. One of the key factors of the NMMPC strategy is to find an appropriate control model for the plant based on the date-driven method. Due to their easy design, good generalization, strong tolerance to input noise, and online learning ability, RBF neural networks have been used in MPC for nonlinear system modeling [34,35]. However, the number of hidden nodes in these RBF neural networks is often assumed to be constant [34,35]. Only the parameters of these RBF neural network models are changed. Unlike some works applied RBF neural networks as the identifier for the MPC system, this proposed SORBF neural network can be used to change both the network structure (the number of hidden nodes) and the parameters (the weights). This characteristic makes the method ideal for complex nonlinear dynamic applications. The SORBF neural network with concurrent structure and parameter learning is used to achieve a compact structure size and model accuracy on-line based on the characteristics of WWTP. Then, the SORBF neural network can be used to replace some existing instruments when unreliable measurements are reported.

Secondly, in the purpose of achieving the effluent quality criterion and minimize the operating costs, a multiobjective optimization problem should be carried out [26,36]. However, the problems involving multiple objectives present additional difficulties since the optimal solution is not as clearly defined as for single objective problems [37,38]. This proposed NMMPC provides a framework for multiobjective control problem which, by inherently embodying the principle of optimality, enables arbitrarily fast implementation of control calculations based upon a multi-gradient method (MGM). This MGM is proposed to handle multiple objectives for NMMPC by providing a more general picture through a fully analytical description of the gradient for multiobjective optimization problems. The multiobjective optimization method is designed to track directly the compromise solution in the cost space instead of weighting the individual objectives as a single objective function. Then, this multiobjective strategy can minimize the multiple objectives simultaneously and provide insight into MGM of MMPC.

Thirdly, as the stability of the proposed control strategy is important for the applications [39–41], NMMPC has been specifically designed with this in mind. The convergence analysis for SORBF identifier and the conditions of the stability analysis of the closed-loop systems are established for NMMPC. Moreover, the convergence to Pareto-optimal solutions has been demonstrated theoretically. The stability of the proposed NMMPC control loop is investigated for deep-understanding the proposed control strategy.

The remainder of this paper is organized as follows. Section 2 defines the problem and necessary conditions. While the SORBF neural network has an efficient model feature introduced in Section 3 together with NMMPC for addressing the modeling and optimizing problems for WWTP. Section 4 discusses the convergence of SORBF models and the stability of the NMMPC scheme. The results of the simulations are presented in Section 5. Meanwhile, several control strategies are proposed for describing the comparisons. Finally, Section 6 concludes the paper.

2. Problem definition

The following notations and definitions will extensively be used throughout the paper. Let R be the real number, R^n and $R^{n\times m}$ represent the real-vectors and the real $n \times m$ matrices, respectively. $||\cdot||$ denotes the usual Euclidean norm of a vector. In the case where y is a scalar, $||y||$ denotes its absolute value and if Y is a matrix, $||Y||$ means Frobenious norm defined as $||Y|| = \sqrt{trace\{Y^TY\}}$, where trace$\{\cdot\}$ stands for trace operator.

2.1. Benchmark of wastewater treatment plants

WWTP is a dynamic system, subject to different physical and biological phenomena, where large disturbances are taking place. Many control strategies have been proposed in the literature for wastewater treatment plants but their evaluation and comparison are difficult. This is partly due to the variability of the influent, to the complexity of the physical and biochemical phenomena and to the large range of time constants inherent in the activated sludge process. A benchmark, i.e. a simulation environment defining a plant layout, a simulation system including influent loads, test procedures and evaluation criteria has been proposed within the framework of COST Actions 682 and 624 – BSM1 [42]. In the BSM1, the plant is lay as Fig. 1 which composed of two anoxic zones, three aerobic zones and a secondary settler. The system for each bioreactor zone is based on the International Association on Water Quality Activated Sludge Model 1 (IAWQ-ASM1) [43].

The complete benchmark model is summarized by the following equations