Neurocomputing ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Adaptive neural control of the dissolved oxygen concentration in WWTPs based on disturbance observer

Mei-Jin Lin [a,*], Fei Luo [b]

[a] Department of Automation, Foshan University, Foshan, Guangdong 528000, China
[b] College of Automation Science and Engineering, South China University of Technology, Guangzhou 510641, China

ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form
23 October 2015
Accepted 17 December 2015
Communicated by Lixian Zhang

Keywords:
Adaptive control
Disturbance observer
Neural networks (NNs)
Dissolved oxygen concentration

ABSTRACT

Dissolved oxygen (DO) concentration is a key variable in the activated sludge wastewater treatment processes. To solve the DO concentration control problem, a neural adaptive control design technique using a disturbance observer is developed. In the controller design, radial basis function (RBF) neural networks (NNs) are used to approximate the uncertain dynamics of the wastewater treatment process. First, the unknown external disturbance and the NN approximation error are combined into a compounded disturbance, and estimated by a nonlinear disturbance observer. Then, rigorously proved by Lyapunov method, the adaptive NN control based on the disturbance observer can guarantee semiglobal uniform boundedness of the closed-loop system signals and the disturbance estimate error. Finally, simulation studies are performed to demonstrate the effectiveness of the proposed controller. Comparing with the existing controllers, it is shown that satisfactory performances can be achieved using the proposed adaptive control technique.

1. Introduction

The aim of wastewater treatment plants (WWTPs) is to treat the wastewater to a level so that natural systems can safely absorb the effluent [1]. For the treatment of the civil wastewater, one of the widely used approaches is the activated sludge process (ASP), which uses microorganisms to remove contaminants. In the ASP, control of process variables, such as the DO concentration, the suspended solid concentration and the ammonia concentration to specified values, plays an important role in improving the treatment operation effectiveness, and has been attracted extensive attentions during the last years.

To keep the process variable at a set-point, the most widely used control technique is the Proportional-Integral-Derivative (PID) algorithm. PID controllers with predetermined design parameter values [2,3], or with parameter tuning methods [4] have been applied in WWTPs. To improve the operational performance, fuzzy logic control (FLC) was also introduced in [5,6]. Most of these controllers did not need detailed information of the process model.

Besides, control design techniques based on the process model have been studied for the activated sludge process, such as controllers in [7,8] integrated the simplified model derived from the Activated Sludge Model No. 1 (ASM1), the control method in [9] based on a linearized process model. The kinetic parameter values and the ideal biological reaction conditions were predetermined in those studies, while such kind of bioprocess is well-known for the large nonlinearities, unknown dynamics and highly coupled variables [10,11]. To overcome the difficulties mentioned above, several control strategies have been developed, such as optimal control [12,13], model predictive control (MPC) [14–18], sliding mode control [19] and adaptive control [10,20,15].

It should be noted that an important concern in the system is how to deal with unknown dynamics, which could be parametric or functional uncertainties [21]. A fuzzy system is a well-known powerful tool, which is capable of dealing with the systems subjected to uncertain dynamics, and has been successfully applied in the bioprocess [18,20]. Another powerful tool is adaptive neural network (NN) control, which is suitable for controlling uncertain and nonlinear systems, due to its universal approximation capabilities and parallel distributed structures [22]. The results of adaptive NN control designs for the ASP can be seen in [23–25]. Besides, in the ASP, some state variables, such as biomass (sludge), substrates and product concentration, are hardly measured online due to the lack or the high cost of the equipments. Therefore, it is very difficult to implement some state-feedback control laws directly in this bioprocess. To overcome this difficulty, different kinds of state observers [26–29] were studied. Moreover, integrations of different methods for improving the operation of WWTPs have received attentions recently [30], such as a nonlinear MPC combined with a NN identifier and a multiobjective

---

* Corresponding author. Tel.: +86 020 6516 2575.
E-mail addresses: lmjfans@163.com (M.-J. Lin), aufeiluo@scut.edu.cn (F. Luo).

http://dx.doi.org/10.1016/j.neucom.2015.12.045
0925-2312/© 2015 Elsevier B.V. All rights reserved.

Please cite this article as: M.-J. Lin, F. Luo, Adaptive neural control of the dissolved oxygen concentration in WWTPs based on disturbance observer, Neurocomputing (2016), http://dx.doi.org/10.1016/j.neucom.2015.12.045

optimization method in [31], and a hierarchical control method with different kinds of controllers in [32].

As mentioned above, control problems of WWTPs have received vast attentions in recent years. However, among these studies, few considered the effects of external disturbances. While many large disturbances exist in the operation of WWTPS, which is caused by many reasons, such as large perturbations in influent flow rate and pollutant load, the changing kinetic parameter values under the influence of internal and external factors, and so on. To estimate the external disturbance, an auxiliary dynamical system or an observer, driven by the inputs and outputs of the original system, has been well studied [33] and applied in a lot of real fields [34,35]. However, to our best knowledge, the external disturbances affecting the activated sludge treatment process are less investigated. Therefore, in this paper, we will study adaptive neural control for the uncertain ASP with unknown time-varying external disturbances.

Due to the strong effects of the DO concentration on the wastewater treatment effectiveness and the operational cost, the DO control problem is concerned in this paper. Firstly, the model with the input oxygen transfer rate (K_{La}) and the output DO concentration (S_o) is derived [36] from ASM1. Due to dynamic uncertainties and large nonlinearities in the model, radial basis function (RBF) neural networks (NNs) are used as approximators in the controller design. The NN approximation error and the unknown external disturbances are combined into a compounded disturbance, and estimated by a nonlinear disturbance observer. Then, rigorously proved by Lyapunov method, the adaptive NN control based on a disturbance observer can guarantee semiglobal uniform boundedness of the closed-loop system signals and the disturbance estimate error. Simulation studies demonstrate the effectiveness of the proposed controller. Comparing with the existing controllers, satisfactory performances can be achieved using the proposed adaptive controllers.

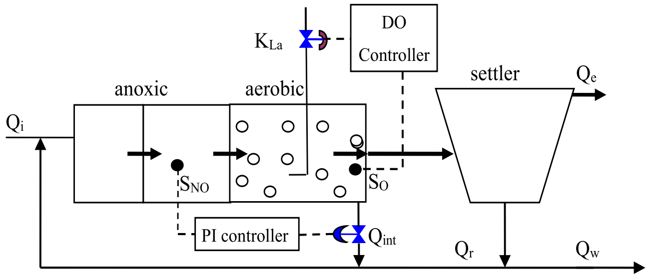
The remainder of this paper is organized as follows. Section 2 briefly introduces the underlying WWTP and develops a reduced model of DO concentration. Then, the control objective and RBF NNs are presented. Section 3 gives an adaptive NN control design based on a disturbance observer, and by Lyapunov method, the proof of uniformly bounded characteristics of the closed-loop system signals and the compounded disturbance estimate error. Numerical simulations are conducted and the related comparison results are given in Section 4. The last section concludes the paper.

2. Problem formulation and preliminaries

The notations used throughout this paper are fairly standard. $\|\bullet\|$ denotes the Euclidean norm of vectors and induced norm of matrices. $\hat{()}$ and $\tilde{()}$ denote the estimate value and the estimate error of an unknown parameter, respectively. $\lambda_{\min}(\bullet)$ and $\lambda_{\max}(\bullet)$ denote the minimum and maximum eigenvalues of a symmetric matrix, respectively.

2.1. Dynamical model of activated sludge process

A wastewater treatment plant considered in this paper is composed of four compartments in series: two anoxic compartments, an aerobic compartment, and a settler. The wastewater influent flow to the plant is treated firstly in anoxic (nitrate present, no oxygen) condition, then in aerobic (oxygen present) condition. Finally, the cleaned wastewater is clarified in the settler. Fig. 1 shows a typical activated sludge WWTP layout, without considering the different pretreatment steps that normally precede the activated sludge compartments.



Q_i: the input flow rate
Q_e: the effluent flow rate
Q_r: the return sludge flow rate
Q_{int}: the internal flow recirculation rate
Q_w: the wastage flow rate
S_O: the dissolved oxygen concentration
K_{La}: the oxygen transfer rate
S_{NO}: the nitrate and nitrite nitrogen concentration

Fig. 1. Schematic view of an activated sludge process.

The ASP is a very complex process, which is highly nonlinear and characterized by uncertainties regarding its parameters. In order to capture as closely as possible the evolution of the ASP, many models were introduced [37]. In this paper, we use ASM1 [36] for the model of biological reactors and sedimentation tank model defined in [38] for the settler.

Generally, ASM1 is a widely accepted model to describe the biological phenomena taking place in the biological reactor. In ASM1, there are 13 mass balance equations and 8 basic processes, which are used to describe the complicated biological relations among 13 different variables. In the ASP, due to strong effects of aeration on biomass growth and the aeration energy cost, the control of the DO concentration receives vast attentions [1]. In this paper, we consider the mass balance equation directly related to DO concentration in the aerobic compartment,

$$\dot{S}_{o3}(t)=\frac{Q_i+Q_r+Q_{\text{int}}}{V_2}S_{o2}(t)-\frac{Q_i+Q_r+Q_{\text{int}}}{V_3}S_{o3}(t)+K_{La}(S_{o,sat}-S_{o3}(t))+\frac{S_{o3}(t)}{K_o+S_{o3}(t)}R_r \tag{1}$$

where $S_{o2}(t)$, $S_{o3}(t)$, $S_{o,sat}$ denote the DO concentration in the second compartment, the DO concentration in the third compartment, and the saturation value of DO, respectively, V_2, V_3 denote the volume of the second and the third compartment, respectively, K_o denotes a kinetic parameter, R_r denotes the respiration rate, K_{La} denotes the oxygen transfer rate which is the control input for the DO concentration model.

In the second compartment, nitrogen removal is a process goal under oxygen-free conditions (i.e., $S_{o2}(t)\approx 0$). Therefore, the value of the first term in the right hand side of Eq. (1) is in a small neighborhood around zero (i.e., $(Q_i+Q_r+Q_{\text{int}})\times S_{o2}(t)/V_2\approx 0$). Therefore, we set

$$d(t)=\frac{Q_i+Q_r+Q_{\text{int}}}{V_2}S_{o2}(t) \tag{2}$$

where $d(t)$ represents an external disturbance when we consider the variable S_o in the third biological reactor and $0\le d(t)\le d_0$ with d_0 being a positive constant.

From Eq. (1), the value of S_{o3} is related to R_r. And R_r is a nonlinear function of some state variables in ASM1. Therefore, it can be induced that the model of R_r can be regarded as a function with nonlinear dynamics and a very high order of S_{o3}. Additionally, the wastewater influent to the plant consists sophisticated information which might only be partially depicted using current modeling techniques, hence the highly nonlinearities, time-varying dynamics in R_r might be too complicated to be used for controller design.

Please cite this article as: M.-J. Lin, F. Luo, Adaptive neural control of the dissolved oxygen concentration in WWTPs based on disturbance observer, Neurocomputing (2016), http://dx.doi.org/10.1016/j.neucom.2015.12.045