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A simple and efficient feedback control strategy for wastewater denitrification

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Abstract: Due to severe mathematical modeling and calibration difficulties open-loop feedforward control is mainly employed today for wastewater denitrification, which is a key ecological issue. In order to improve the resulting poor performances a new model-free control setting and its corresponding “intelligent” controller are introduced. The pitfall of regulating two output variables via a single input variable is overcome by introducing also an open-loop knowledge-based control deduced from the plant behavior. Several convincing computer simulations are presented and discussed.

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1. INTRODUCTION

Maintaining low nitrite concentrations in the effluent is a major ecological issue for wastewater treatment plants (WWTP) due to nitrite's high toxicity (see, e.g., Capodaglio *et al.* (2016); Fux *et al.* (2015); Grady Jr. *et al.* (2011); Henze *et al.* (2008); Raimonet *et al.* (2015); Water Environment Federation (2013)). To this end, the aim of a wastewater post-denitrifying biofilter is to convert nitrate and nitrite (NO_x , $x = 2, 3$) of the effluent into nitrogen gas (N_2). The process uses a submerged packed bed biofilm reactor hosting a class of bacteria under anoxic (low/no oxygen) conditions which use the NO_x as a source of oxygen when they are fed with a carbon source such as methanol (Samie *et al.* (2011); Bernier *et al.* (2014)). On the one hand, underfeed of methanol will limit the reduction of NO_x in the process, and as the denitrification is a two step reaction $\text{NO}_3 \rightarrow \text{NO}_2 \rightarrow \text{N}_2$, this can leave some nitrite in the effluent even if this compound was absent in the influent (Rocher *et al.* (2015)). On the other hand, overfeed of methanol results in elevated effluent biochemical

oxygen demand (BOD) and useless operating expenses. In most WWTP using post-denitrifying biofilters, the actual control strategy is mainly of feedforward open-loop type: ¹ on-line measurements of incoming NO_x are combined with wastewater flow to compute an ideal methanol feed rate. But because of process complexity and many types of disturbances, e.g., periodical backwash of biofilters, this is not sufficient to accurately control the nitrite concentration in the effluent. Model-based approaches seem nevertheless to be hard to apply in this context (see, e.g., Grady Jr. *et al.* (2011); Water Environment Federation (2013)). In fact the dynamics of a denitrifying biofilter has to be described by partial differential equations taking into account concentration gradients, nonlinearities of the biological processes, biofilm clogging and so on (see, e.g., the excellent report by Dochain *et al.* (2001), and the references therein). Such an exhaustive model needing the identification of numer-

¹ See, e.g., Bastin *et al.* (1990); Bourrel *et al.* (2000); Cristea *et al.* (2008); Marsili-Libelli *et al.* (2002); Olsson *et al.* (1999); Torres Zúñiga *et al.* (2012); Wahaba *et al.* (2009) for most interesting exceptions, i.e., for the use of feedback loops

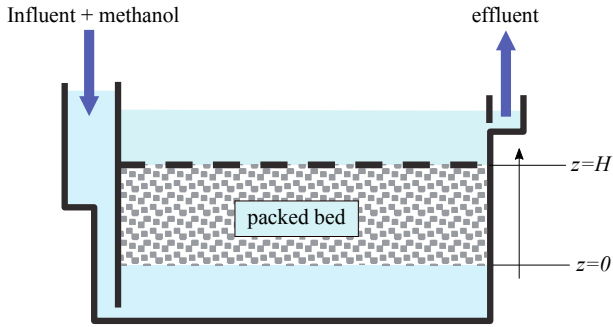


Fig. 1. Packed bed denitrifying biofilter

ous parameters is necessary to assess a particular control strategy, like in Section 4. However it cannot reasonably be used for realtime feedback control.

A new *model-free control* setting (Fliess *et al.* (2013)) is therefore used.² The corresponding *intelligent P* feedback controller is moreover quite easy to implement both from software (Fliess *et al.* (2013)) and hardware (Join *et al.* (2013)) standpoints. Many concrete applications have already been developed all over the world. Some have been patented. Lack of space permits here to quote only three recent works that are related to biotechnology: Bara *et al.* (2016); Lafont *et al.* (2015); Tebbani *et al.* (2016). From a purely control-theoretic viewpoint, a major difficulty is encountered: a single input variable must regulate two output variables (see, *e.g.*, Fliess (1989) for an explanation via input-output nonlinear system inversion). A satisfactory practical solution is nevertheless proposed. It is based on an appropriate mixing of a knowledge-based behavior of the plant with a suitable feedback law.

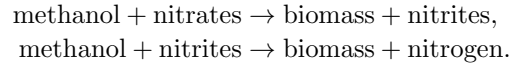
Our paper is organized as follows. Section 2 is sketching wastewater treatment and its corresponding rough description via differential equations. Model-free control and the associated real-time estimation techniques are summarized in Section 3. After presenting our control law, Section 4 displays convincing computer experiments, which are based in this preliminary work on the modeling in Section 2. Some concluding remarks may be found in Section 5.

2. PROBLEM AND MODEL

2.1 Dynamic model of the biofilter

The actual denitrifying process is composed of several biofilters operating in parallel with the same influent. A typical unit is displayed in Figure 1. The water is fed from the base of the filter bed, which is composed of beads of expanded clay. A biofilm, where all biological reactions occur, is considered to grow on the media. The biological reactions inside the biofilm are modeled using a modified version of ASM1 (Henze *et al.* (1987)). This model is widely used to simulate the growth of bacteria and the resulting consumption of carbon and nitrogen pollution occurring in biological wastewater treatment processes. The main modification in this specific case consists in

the addition of two-step denitrification to simulate the production and consumption of nitrite during the process. The first two denitrification reactions of ASM1 (Hiatt *et al.* (2008)) were used to this end, and can be summarized as



The whole dynamics of the biofilter results from the mass balance of the different reacting species, nitrate S_1 , nitrite S_2 , carbon S_C and biomass X . The limited axial dispersion allows to consider that all concentrations are constant in a vertical cross section. The following model with distributed parameters, *i.e.*, a system of partial differential equations, model with a single space dimension, may be written

$$\varepsilon \partial_t S_1 = -v \partial_z S_1 - k_1 \mu_1(S_1, S_C) X \quad (1)$$

$$\varepsilon \partial_t S_2 = -v \partial_z S_2 + k_1 \mu_1(S_1, S_C) X - k_2 \mu_2(S_2, S_C) X \quad (2)$$

$$\varepsilon \partial_t S_C = -v \partial_z S_C - k_3 \mu_1(S_1, S_C) X - k_4 \mu_2(S_2, S_C) X \quad (3)$$

$$\partial_t X = (\mu_1(S_1, S_C) + \mu_2(S_2, S_C))(1 - X/X_{\max}) X \quad (4)$$

for $z \in]0, H[$. All species concentrations are given in g/m^3 . The yield coefficients $(k_i)_{i=1,\dots,4}$ are given in g/g , the superficial velocity v in m/h (flow rate in m^3/h divided by the cross-section area) and ε is the porosity. The specific growth rates μ_1 and μ_2 are given by a double Monod-type model (Bastin *et al.* (1990))

$$\mu_i(S_i, S_C) = \mu_{i,\max} \frac{S_i S_C}{(K_i + S_i)(K_C + S_C)} \quad i = 1, 2$$

where $\mu_{i,\max}$ is the maximum specific growth rate for species S_i and K_i, K_C the affinity constants. The boundary conditions are given by

$$S_1(0, t) = S_{1,in}(t), S_2(0, t) = S_{2,in}(t), S_C(0, t) = S_{C,in}(t)$$

where $S_{C,in}(t)$ is the methanol concentration at the inlet of the reactor, *i.e.* the control variable.

Equations (1)-(4) were initially proposed for a drinkable water denitrifying biofilter (see (Bourrel *et al.* (2000))) and were easily adapted to our specific configuration as only hydraulic parameters and maximum biomass concentration X_{\max} had to be changed. They have been used during the early stage of our project in order to validate our interest for model-free control, but the simulations of Section 4 have been made with the *SimBio* software. This more realistic setting is built in Matlab with the Simulink toolbox, using submodels already available in the literature. The biofilter hydraulics is approximated with a series of several continuously stirred tank reactors (CSTRs) of equal volume to obtain reactor hydraulics close to the plug-flow model of equations (1)-(3) while maintaining simulation times in a reasonable range. As concentration gradients are observed in thick biofilms, their distributed nature is taken into account in *SimBio* by dividing the biofilm into several CSTRs through which soluble substrates are able to diffuse (Spengel *et al.* (1992)). Soluble substrates are brought to and into the biofilm through diffusion, whereas particular components are transferred to the biofilm surface through filtration (Horner *et al.* (1986); Ives (1970)). Backwash efficiency is modelled as a removal of a fixed proportion of biofilm thickness in each reactor using different removal efficiencies for biomass and for other non-biomass particles. A certain fraction of media mixing among the reactors also occurs during backwash.

² See, *e.g.*, Join *et al.* (2010) for the analysis of model-free control in a somehow analogous situation with respect to partial differential equations.

This version of *SimBio* was calibrated on hourly nitrate and nitrite measurements made on the post-denitrification step of the Seine-Centre plant (Bernier *et al.* (2014)).

2.2 Actual control strategy on the real plant

The control variable value $S_{c,in}(t)$ is tuned according to a desired removal of incoming nitrogen, which comes under the form of nitrates (the incoming concentration of nitrite is negligible), *i.e.*, for a target concentration of $S_{1,target}$ at the outlet of the reactor, the control law is of the form

$$S_{c,in}(t) = \beta(S_{1,in}(t) - S_{1,target}) \quad (5)$$

where β is an operating coefficient based on pure stoichiometric and yield considerations (Rocher *et al.* (2015)). This strategy does not take into account the intermediate species (nitrite) and leads to an unstable behavior of its concentration in the effluent. In fact the ratio between the methanol and the total nitrogen (nitrate and nitrite) concentrations in the biofilter plays a major role in the appearance of residual nitrites, but it cannot be controlled with a simple control law as in Equation (5). However, as the nitrite concentration can be measured at the outlet of the biofilter, it can be used as a natural controlled variable in a feedback control strategy.

3. MODEL-FREE CONTROL

3.1 The ultra-local model

Replace the unknown global system description by the *ultra-local model*:³

$$\dot{y} = F + \alpha u \quad (6)$$

where

- the control and output variables are u and y ,
- the derivation order of y is 1 like in most concrete situations,
- $\alpha \in \mathbb{R}$ is chosen by the practitioner such that αu and \dot{y} are of the same magnitude.

The following explanations on F might be useful:

- F is estimated via the measures of u and y ,
- F subsumes not only the unknown system structure but also any perturbation.

Remark 3.1. In Equation (6) \dot{y} is seldom replaced by \ddot{y} (see, *e.g.*, Fliess *et al.* (2013), and the references therein). Higher order derivatives were never utilized until today.

3.2 Intelligent controllers

The loop is closed by an *intelligent proportional controller*, or *iP*,

$$u = -\frac{F - \dot{y}^* + K_P e}{\alpha} \quad (7)$$

where

- y^* is a reference trajectory,
- $e = y - y^*$ is the tracking error,
- K_P is the usual tuning gain.

³ For more details, see Fliess *et al.* (2013).

Combining Equations (6) and (7) yields:

$$\dot{e} + K_P e = 0$$

where F does not appear anymore. The tuning of K_P , in order to insure local stability, becomes therefore quite straightforward. This is a major benefit when compared to the tuning of “classic” PIDs (see, *e.g.*, Åström *et al.* (2006, 2008), and the references therein), which

- necessitate a “fine” tuning in order to deal with the poorly known parts of the plant,
- exhibit a poor robustness with respect to “strong” perturbations and/or system alterations.

3.3 Estimation of F

The calculations below stem from algebraic estimation techniques that are borrowed from Fliess *et al.* (2003, 2008), and Sira-Ramírez *et al.* (2014).

First approach The term F in Equation (6) may be assumed to be “well” approximated by a piecewise constant function F_{est} (see, *e.g.*, Godement (1998)). Rewrite then Equation (6) in the operational domain (see, *e.g.*, Erdélyi (1962)):

$$sY = \frac{\Phi}{s} + \alpha U + y(0)$$

where Φ is a constant. We get rid of the initial condition $y(0)$ by multiplying both sides on the left by $\frac{d}{ds}$:

$$Y + s \frac{dY}{ds} = -\frac{\Phi}{s^2} + \alpha \frac{dU}{ds}$$

Noise attenuation is achieved by multiplying both sides on the left by s^{-2} . It yields in the time domain the realtime estimate, thanks to the equivalence between $\frac{d}{ds}$ and the multiplication by $-t$,

$$F_{\text{est}}(t) = -\frac{6}{\tau^3} \int_{t-\tau}^t [(\tau - 2\sigma)y(\sigma) + \alpha\sigma(\tau - \sigma)u(\sigma)] d\sigma \quad (8)$$

Second approach Close the loop with the iP (7):

$$F_{\text{est}}(t) = \frac{1}{\tau} \left[\int_{t-\tau}^t (\dot{y}^* - \alpha u - K_P e) d\sigma \right] \quad (9)$$

Remark 3.2. Note the following facts:

- integrals (8) and (9) are low pass filters,
- $\tau > 0$ might be quite small,
- the integrals may of course be replaced in practice by classic digital filters.

4. NUMERICAL EXPERIMENTS

4.1 Control law description

Our control law is displayed by Figure 2:

- Equation (5) defines the single control variable in open loop,
- the loop is closed via the iP (7).

The aim of methanol injection $S_{c,in}$, *i.e.*, our single input variable,⁴ is to regulate the total nitrogen concentration,

⁴ See Section 2.1 for precise definitions of the quantities associated to the letter S .

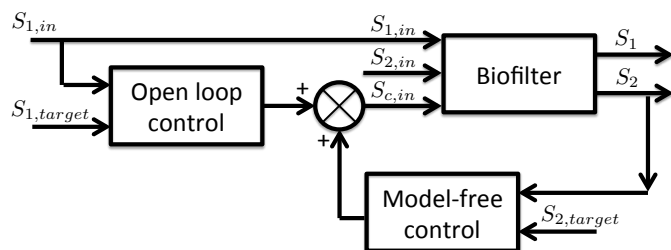


Fig. 2. Control scheme

i.e., two quantities S_1 and S_2 , namely the nitrate and nitrite wastewater concentrations. The fact, depicted in Figure 3, that S_1 is much larger than S_2 , is taken into account by regulating S_1 via an open-loop knowledge-based control. For S_2 model-free control is utilized. For Equations (6)-(7), $\alpha = 1$ and $K_p = 100$ were selected. In order to avoid debating the regulation of S_1 the resulting value of the iP should be non-negative. If not, the water concentration of nitrate would increase. This is not acceptable.

4.2 Simulations

The mathematical modeling discussed in Section 2.1 is used for the computer simulations. The sampling time period is 0.001 day.

Quite good results corresponding to several targets are displayed in Figures 4, 5, 6, 7, 8. Important daily perturbations, corresponding to biofilter backwash, have been introduced in order to show more realistic performances. According to the Figures, a small injection of methanol is reducing notably the nitrites and nitrates concentrations in the water which is rejected. Notice however a worsening of the performances if $S_{2,target} \geq 1.2$. Let us emphasize that

- it is not due to a weakness of our control strategy,
- the very nature of the wastewater denitrification, which is detailed at the end of Section 4.1, explains it.

5. CONCLUSION

This new setting for wastewater denitrification, which seems to be rather promising (see Rocher *et al.* (2017) for further details), will soon be tested in Paris. Although it has been shown in other applications that model-free control behaves quite well with respect to noise corruptions, it will provide us with more realistic data on noisy measurements, and other perturbations, for water treatment. The results will be reported elsewhere.

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⁵ MOCOPÉE is an acronym of the French words ‘MOdélisation Contrôle et Optimisation des Procédés d’Epuración des Eaux.’

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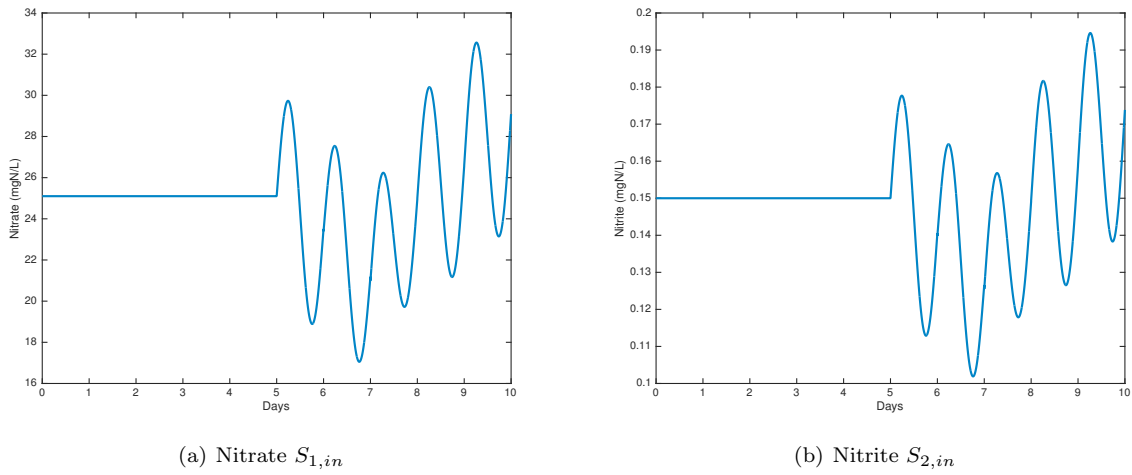


Fig. 3. Influent

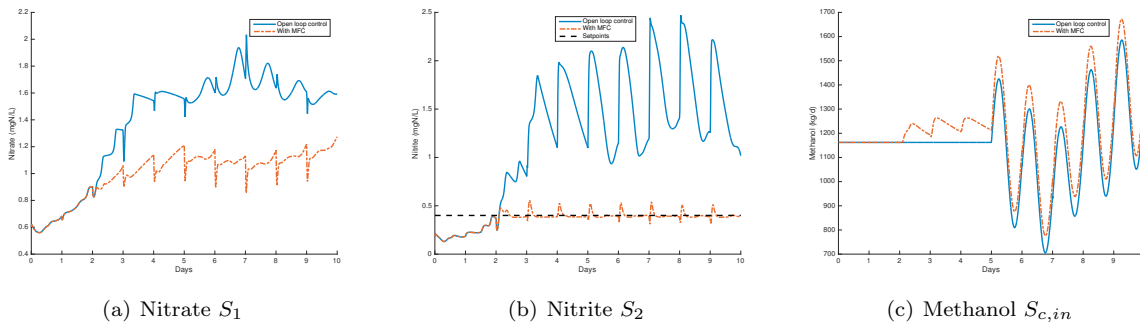


Fig. 4. Setpoint : $S_{2,target} = 0.4$

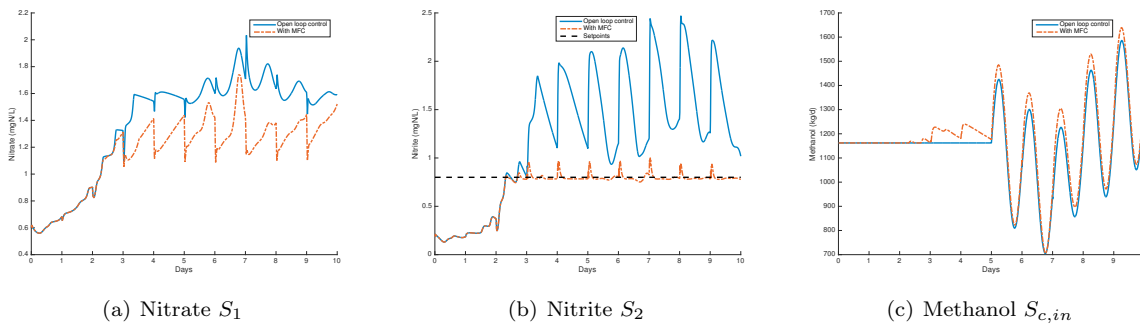


Fig. 5. Setpoint : $S_{2,target} = 0.8$

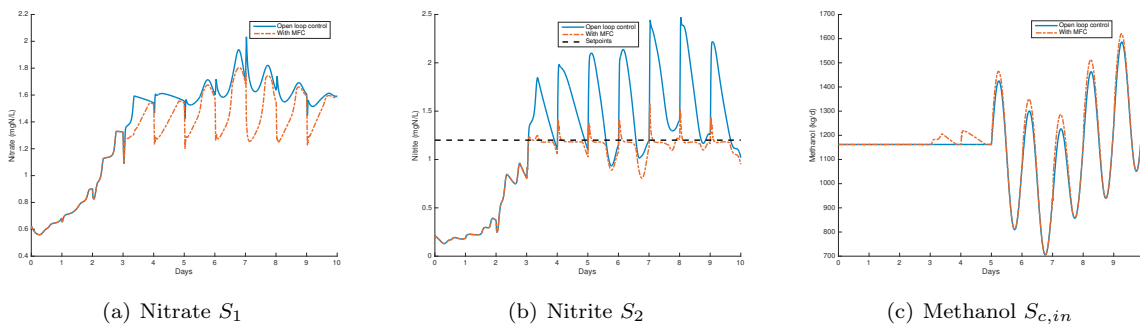
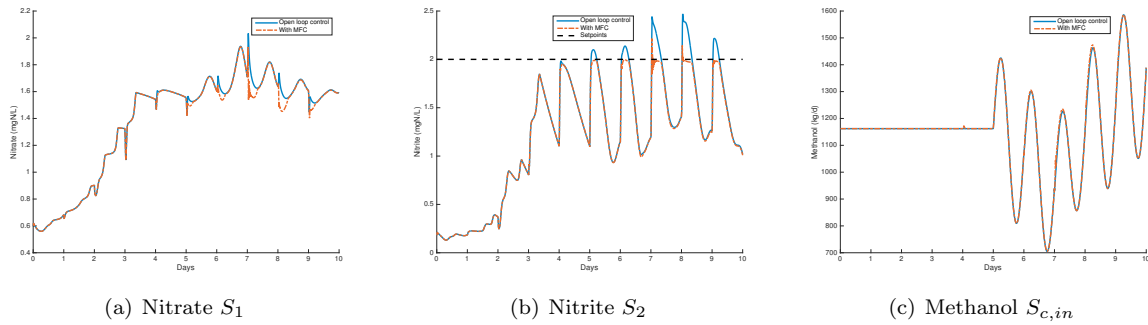
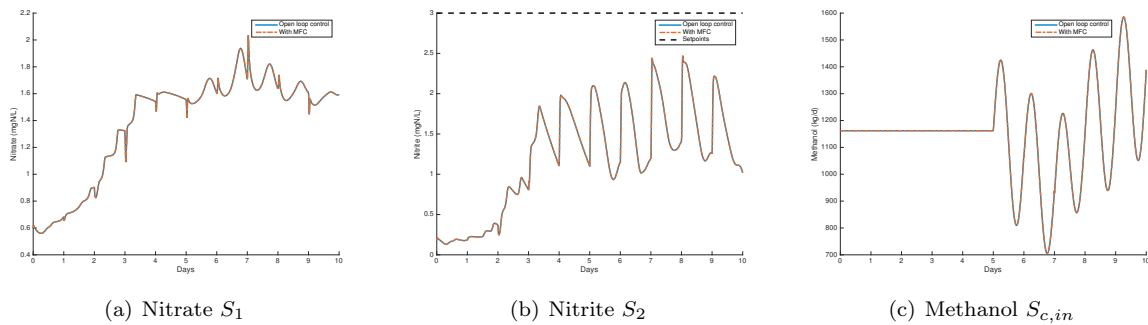


Fig. 6. Setpoint : $S_{2,target} = 1.2$

Fig. 7. Setpoint : $S_{2,target} = 2.0$ Fig. 8. Setpoint : $S_{2,target} = 3.0$

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