Predictive Control of a Nutrient Removal Biological Plant

Fatiha Nejjari & Joseba Quevedo
UPC University, Department of ESAII
TR11, Rambla Sant Nebridi, 10, Terrassa, Spain
email: fatiha.nejjari@upc.es

***Abstract*— The aim of this work is to estimate and control a biological nitrogen and carbon removal process. The paper illustrates the use of a complex nonlinear model in the design of a software sensor and a predictive control techniques. Process modeling describes the complete dynamics of autotrophic and heterotrophic biomasses, biodegradable organic and nitrogenous matters. The control approach structure is combined with the estimation algorithm, for the on-line reconstruction of unmeasured biological states and unknown parameters of the bioprocess. The efficiency of both the control and estimation schemes are demonstrated via computer simulations.**

I. INTRODUCTION

The modeling and control of activated sludge process, which is recognized as the most common and major unit process for reduction of organic waste, has become a subject of greater interest. Researchers [1], [2], [6], [5], [4], have investigated different control strategies for the monitoring of such processes. The development of effective control strategies on this kind of Wastewater Treatment Process (WWTP) is hampered by the inherent nonlinearity and time-varying dynamics of such processes and the lack of suitable instrumentation.

The main feature of the activated sludge process (ASP) includes degradation of influent biodegradable pollutants, containing both organic carbon and nitrogen by use of microorganisms. The organisms form flocs which are separated from the treated wastewater by means of gravity settling and recirculated back to the reactors. Basically, organic material is transformed into water and carbon-dioxide by heterotrophic organisms while consuming oxygen (aerobic conditions) or nitrate (anoxic conditions). Nitrogen (in the form of ammonia) is transformed into nitrate and water by autotrophic organisms while utilizing oxygen (aerobic conditions). However, the carbonaceous and nitrogenous material are present in many different forms, which the microorganisms react differently to and they are also transformed between forms through hydrolysis. Moreover, a large number of different organisms species exist within an ASP and the dominating population may change over time. Consequently, the behaviour of a plant varies. The process is also affected by the oxygen requirements, hydraulic flow schemes, the behaviour of the settler, as well as the environmental parameters, such as temperature, pH, and toxic or inhibitory substances.

In this paper, modeling, estimation and control of a nutrient removal plant are considered. The main scope of the modeling is to describe the dynamics of the components concentrations in the plant. Population dynamics for microorganisms are defined by different equations for each type of biomass (nitrifyers/autotrophics and denitrifyers/heterotrophics). The resulting system is strongly non-linear.
As activated sludge is a highly complex system which is caracterised by a limited number of control possibilities and available on-line measurements, the need of better understanding of the dynamics of this system and overcomimg its sensor lack is stressed. The control law is based on direct exploitation of the non linear model representing the wastewater treatment process and is coupled with an asymptotic estimator for on line tracking of simultaneously unavailable states and time varying parameters. The estimated variables are used in the explicit design of the control algorithm according to the certainty equivalence principle.

The paper is organized as follows. The modeling of the continuous WWTP is detailed in section II. Section III is dedicated to the estimation of both unavailable states and parameters of the process. The control law is then described in section IV. Section V deals with simulation studies.

II. MODELING OF THE ACTIVATED SLUDGE PROCESS

A typical, conventional activated sludge plant for the removal of carbonaceous and nitrogen materials consists of an anoxic basin followed by an aerated one, which is aerated by a submerged air bubble system or mechanical agitation at its surface, and a settler. In the presence of dissolved oxygen, wastewater, that is mixed with the returned activated sludge, is biodegraded in the reactor. Treated effluent is separated from the sludge in the settler. A portion of the activated sludge is wasted while a large fraction is returned to anoxic reactor to maintain the appropriate substrate-to-biomass ratio.

In this study we consider six basic components present in the wastewater : autotrophic bacteria X_A, heterotrophic bacteria X_H, readily biodegradable carbonaceous substrates

S_S, nitrogen substrates S_{NH}, S_{NO} and dissolved oxygen S_O.

In the formulation of the model the following assumptions are considered: the physical properties of fluid are constant; there is no concentration gradient across the vessel; substrates and dissolved oxygen are considered as rate-limiting with a bi-substrate Monod-type kinetic; no bioreaction takes place in the settler and the settler is perfect.

Based on the above description and assumptions, we can formulate the full set of ordinary differential equations (mass balance equations), making up the IAWQ AS Model NO.1 [3].

A. Modeling of the aerated basin

$$\begin{aligned}\dot{X}_{A,nit}(t) = (1+r_1+r_2)D_{nit}(X_{A,denit}-X_{A,nit})+\\ (\mu_{A,nit}-b_A)X_{A,nit}\end{aligned} \quad (1)$$

$$\begin{aligned}\dot{X}_{H,nit}(t) = (1+r_1+r_2)D_{nit}(X_{H,denit}-X_{H,nit})+\\ (\mu_{H,nit}-b_H)X_{H,nit}\end{aligned} \quad (2)$$

$$\begin{aligned}\dot{S}_{S,nit}(t) = (1+r_1+r_2)D_{nit}(S_{S,denit}-S_{S,nit})-\\ (\mu_{H,nit}+\mu_{Ha,nit})\frac{X_{H,nit}}{Y_H}\end{aligned} \quad (3)$$

$$\begin{aligned}\dot{S}_{NH,nit}(t) = (1+r_1+r_2)D_{nit}(S_{NH,denit}-S_{NH,nit})-\\ (i_{XB}+\frac{1}{Y_A})\mu_{A,nit}X_{A,nit}-(\mu_{H,nit}+\mu_{Ha,nit})i_{XB}X_{H,nit}\end{aligned} \quad (4)$$

$$\begin{aligned}\dot{S}_{NO,nit}(t) = (1+r_1+r_2)D_{nit}(S_{NO,denit}-S_{NO,nit})+\\ \mu_{A,nit}\frac{X_{A,nit}}{Y_A}-\frac{1-Y_H}{2.86Y_H}\mu_{Ha,nit}X_{H,nit}\end{aligned} \quad (5)$$

$$\begin{aligned}\dot{S}_{O,nit}(t) &= (1+r_1+r_2)D_{nit}(S_{O,denit}-S_{O,nit})\\ &+a_0Q_{air}(C_S-S_{O,nit})-\frac{4.57-Y_A}{Y_A}\mu_{A,nit}X_{A,nit}\\ &-\frac{1-Y_H}{Y_H}\mu_{Ha,nit}X_{H,nit}\end{aligned} \quad (6)$$

Where: $\mu_{A,nit}=\mu_{max,A}\frac{S_{NH,nit}}{(K_{NH,A}+S_{NH,nit})}\frac{S_{O,nit}}{(K_{O,A}+S_{O,nit})}$

$\mu_{H,nit}=\mu_{max,H}\frac{S_{S,nit}}{(K_S+S_{S,nit})}\frac{S_{NH,nit}}{(K_{NH,H}+S_{NH,nit})}\frac{S_{O,nit}}{(K_{O,H}+S_{O,nit})}$

$\mu_{Ha,nit}=\mu_{max,H}\frac{S_{S,nit}}{(K_S+S_{S,nit})}\frac{S_{NH,nit}}{(K_{NH,H}+S_{NH,nit})}\frac{K_{O,H}}{(K_{O,H}+S_{O,nit})}$
$\cdot\frac{S_{NO,nit}}{(K_{NO}+S_{NO,nit})}\eta_{NO}$

$\mu_{A,nit}$ and $\mu_{H,nit}$ are the growth rates of autotrophs and heterotrophs in aerobic conditions and $\mu_{Ha,nit}$ is the growth rate of heterotrophs in anoxic conditions.

B. Modeling of the anoxic basin

$$\begin{aligned}\dot{X}_{A,denit}(t) &= D_{denit}(X_{A,in}+r_1X_{A,nit})+\alpha r_2D_{denit}X_{rec}\\ &-(1+r_1+r_2)D_{denit}X_{A,denit}+(\mu_{A,denit}-b_A)X_{A,denit}\end{aligned} \quad (7)$$

$$\begin{aligned}\dot{X}_{H,denit}(t) &= D_{denit}(X_{H,in}+r_1X_{H,nit})+(1-\alpha)r_2D_{denit}X_{rec}\\ &-(1+r_1+r_2)D_{denit}X_{H,denit}+(\mu_{H,denit}-b_H)X_{H,denit}\end{aligned} \quad (8)$$

$$\begin{aligned}\dot{S}_{S,denit}(t) &= -(\mu_{H,denit}+\mu_{Ha,denit})\frac{X_{H,denit}}{Y_H}\\ &+D_{denit}(S_{S,in}+r_1S_{S,nit})-(1+r_1+r_2)D_{denit}S_{S,denit}\end{aligned} \quad (9)$$

$$\begin{aligned}\dot{S}_{NH,denit}(t) &= D_{denit}(S_{NH,in}+r_1S_{NH,nit})\\ &-(1+r_1+r_2)D_{denit}S_{NH,denit}\\ &-(\mu_{H,denit}+\mu_{Ha,denit})i_{XB}X_{H,denit}\\ &-(i_{XB}+\frac{1}{Y_A})\mu_{A,denit}X_{A,denit}\end{aligned} \quad (10)$$

$$\begin{aligned}\dot{S}_{NO,denit}(t) &= D_{denit}(S_{NO,in}+r_1S_{NO,nit})\\ &-(1+r_1+r_2)D_{denit}S_{NO,denit}+\frac{\mu_{A,denit}X_{A,denit}}{Y_A}\\ &-\frac{1-Y_H}{2.86Y_H}\mu_{Ha,denit}X_{H,denit}\end{aligned} \quad (11)$$

$$\dot{S}_{O,denit}(t) = 0 \quad (12)$$

Where: $\mu_{A,denit}=\mu_{max,A}\frac{S_{NH,denit}}{(K_{NH,A}+S_{NH,denit})}$

$\mu_{H,denit}=\mu_{max,H}\frac{S_{S,denit}}{(K_S+S_{S,denit})}\frac{S_{NH,denit}}{(K_{NH,H}+S_{NH,denit})}$

$\mu_{Ha,denit}=\mu_{max,H}\frac{S_{S,denit}}{(K_S+S_{S,denit})}\frac{S_{NH,denit}}{(K_{NH,H}+S_{NH,denit})}\frac{S_{NO,denit}}{(K_{NO}+S_{NO,denit})}\eta_{NO}$

C. Modeling of the settler

$$\begin{aligned}\dot{X}_{rec}(t) &= (1+r_2)D_{dec}(X_{A,nit}+X_{H,nit})\\ &-(r_2+w)D_{dec}X_{rec}\end{aligned} \quad (13)$$

r_1, r_2 and w represent respectively, the ratio of the internal recycled flow Q_{r1} to the influent flow Q_{in}, the ratio of the recycled flow Q_{r2} to the influent flow and the ratio of waste flow Q_w to influent flow, C_S is the maximum dissolved oxygen concentration. D_{nit}, D_{denit} and D_{dec} are the dilution rates in respectively, nitrification, denitrification basins and settler tank; X_{rec} is the concentration of recycled biomass. The other variables and parameters of the system equations (1)-(13) are defined in section V.

III. Estimation of inaccessible variables

The dynamics of the activated sludge are rewritten in the following manner:

$$\dot{\zeta} = K\varphi(\zeta) - D(t)\zeta(t) + F(t) \tag{14}$$

where:
$\zeta(t) = [X_{A,nit} X_{H,nit} S_{S,nit} S_{NH,nit} S_{NO,nit} S_{O,nit} X_{A,denit} X_{H,denit} S_{S,denit} S_{NH,denit} S_{NO,denit} X_{rec}]^T$ represents the state vector, $\varphi(\zeta)$ is the vector of reaction kinetics, K corresponds to the yield coefficients matrix, D is the matrix of dilution rates and $F(t)$ is the feed rate vector. The state vector is partitioned into: $\zeta = (\zeta_m, \zeta_e)$ with the corresponding matrices and vectors (K_m, D_m, F_m) and (K_e, D_e, F_e) which leads to a full rank coefficients matrix. Then we introduce the following state transformation:

$$Z(t) = A_0 \zeta_m(t) + \zeta_e(t) \tag{15}$$

where A_0 is the solution of the matrix equation:

$$A_0 K_m + K_e = 0 \tag{16}$$

In this case $\zeta_m = [S_{NH,*}, S_{NO,*}, S_{O,*}]$ is the vector of available states and $\zeta_e = [X_{A,*}, X_{H,*}, S_{S,*}, X_{rec}]$ is the vector of unmeasured variables. $* = nit, denit$
The dynamics of the system in the new state space are governed by the following differential equation:

$$\dot{Z} = -A_0 D_m \zeta_m - D_e(Z - A_0\zeta_m) + A_0 F_m + F_e \tag{17}$$

According to [1], an asymptotic observer for the reconstruction of the non measured state variables is then given by:

$$\begin{cases} \dot{\hat{Z}} = -(A_0 D_m - D_e A_0)\hat{\zeta}_m - D_e \hat{Z} + (A_0 F_m + F_e) \\ \hat{\zeta}_e(t) = \hat{Z}(t) - A_0 \zeta_m(t) \end{cases} \tag{18}$$

For the estimation of the specific growth rates, we suppose that the vector of reaction kinetics is partially unknown [1], [2] and written as follows:

$$\varphi(\zeta) = H(\zeta)\mu(\zeta) \tag{19}$$

Where $H(\zeta)$ is the matrix of known functions of ζ and $\mu(\zeta)$ is a vector of unknown functions of ζ.

Under these assumptions, the asymptotic estimation algorithm is given by:

$$\begin{cases} \dot{\hat{\zeta}} = KH(\zeta)\hat{\mu}(\hat{\zeta}) - D\hat{\zeta}(t) + F(t) - \Omega(\zeta_m(t) - \hat{\zeta}_m(t)) \\ \dot{\hat{\mu}} = \Gamma(\zeta_m(t) - \hat{\zeta}_m(t)) \end{cases} \tag{20}$$

The gain matrices Ω and Γ are chosen so that the matrix $\Omega^T\Gamma + \Gamma\Omega$ is non negative definite.

IV. Regulation of global nitrogen and dissolved oxygen concentrations

A primary objective of the activated sludge operation is to maintain the effluent organics concentration below certain regulatory limits. A multivariable predictive control strategy based on NH_4, NO_3 and O_2 measurements is developed, enabling the control of the nitrogen and the dissolved oxygen concentrations, by acting on the internal recycled flow and aeration flow rates, Q_{r1} and Q_{air}, at desired levels.
We define the variable y as the global nitrogen concentration.

$$y = S_{NH,nit} + S_{NO,nit}$$

Using the Euler formula with a sampling period T_s, the model equations 4, 5 and 6 are discretized to yield a one-step-ahead predictor as follows:

$$\begin{aligned} y^{prd}(k+1) &= y^m(k)\left(1 - T_s(1 + r_1 + r_2)D_{nit}(k)\right) \\ &+ T_s(S_{NH,denit} + S_{NO,denit})(1 + r_1 + r_2)D_{nit}(k) \\ &- T_s R_1(k) \end{aligned} \tag{21}$$

$$\begin{aligned} S^{prd}_{O,nit}(k+1) &= S^m_{O,nit}(k)\left(1 - T_s(1 + r_1 + r_2)D_{nit}(k)\right) \\ &+ T_s a_0 Q_{air}(k)(C_s - S^m_{O,nit}(k)) + T_s R_2(k) \end{aligned} \tag{22}$$

where:

$$\begin{aligned} R_1(k) &= (i_{XB} + \tfrac{1-Y_H}{2.86Y_H})\mu_{Ha,nit}(k) X_{H,nit}(k) \\ &+ i_{XB}\mu_{A,nit}(k) X_{A,nit} + i_{XB}\mu_{H,nit}(k) X_{H,nit}(k) \end{aligned}$$

$$\begin{aligned} R_2(k) &= (1 - \tfrac{4.57}{Y_A})\mu_{A,nit}(k) X_{A,nit}(k) \\ &+ (1 - \tfrac{1}{Y_H})\mu_{Ha,nit}(k) X_{H,nit}(k) \end{aligned}$$

$y^{prd}(k+1) = S^{prd}_{NH,nit}(k+1) + S^{prd}_{NO,nit}(k+1)$ is the predicted value of y(k) at the instant k+1.

We suppose that: $Q_{r1} = r_1 Q_{in}$, $Q_{r2} = r_2 Q_{in}$, $Q_w = wQ_{in}$, $D_{nit} = \frac{Q_{in}}{V_{nit}}$, $D_{denit} = \frac{Q_{in}}{V_{denit}}$ and $D_{dec} = \frac{Q_{in}}{V_{dec}}$.

Let the reference model squaring with asymptotic attenuation of the regulation error at a rate defined by the control gain parameters g_1 and g_2 be:

$$y^{mdr}(k+1) = y^*(k) + (1 - g_1)(y^m(k+1) - y^*(k)) \tag{23}$$

$$S^{mdr}_{O,nit}(k+1) = S^*_{O,nit}(k) + (1 - g_2)(S^m_{O,nit}(k+1) - S^*_{O,nit}(k)) \tag{24}$$

with: $0 < g_1 < 1$ and $0 < g_2 < 1$.

Setting at each sampling time, the one-step-ahead predictor for the nitrogen concentration y equal to the prescribed concentration level y* yields the following control law :

$$Q_{r1}(k) = \frac{-V_{nit}(g_1(y^m(k) - y^*) - T_S\hat{R}_1(k))}{T_s(S_{NH,denit}(k) + S_{NO,denit}(k) - y^m(k))} - (Q_{in} + Q_{r2}) \tag{25}$$

With:

$$\hat{R}_1(k) = (i_{XB} + \tfrac{1-Y_H}{2.86Y_H})\hat{\mu}_{Ha,nit}(k)\hat{X}_{H,nit}(k) + i_{XB}\hat{\mu}_{A,nit}(k)\hat{X}_{A,nit} + i_{XB}\hat{\mu}_{H,nit}(k)\hat{X}_{H,nit}(k)$$

$\hat{X}_{H,nit}(k)$, $\hat{X}_{A,nit}(k)$, $\hat{\mu}_{A,nit}(k)$, $\hat{\mu}_{H,nit}(k)$, and $\hat{\mu}_{Ha,nit}(k)$ are estimated values of simultaneously autotroph biomass, heterotroph biomass and the specific growth rates. They are updated by the asymptotic estimator algorithm and provided to the controller according to the certainty equivalence principle.

In practice, the control action is obviously constrained by the operating conditions.

$$Q_{r1,min} < Q_{r1}(k) < Q_{r1,max} \tag{27}$$

Therefore, the control algorithm is as follows :

$$Q_{r1}(k) = \begin{cases} Q_{r1,min} & \text{if } Q_{r1}(k) < Q_{r1,min} \\ Q_{r1,max} & \text{if } Q_{r1}(k) > Q_{r1,max} \\ Q_{r1}(k) & \text{otherwise} \end{cases} \tag{28}$$

Once $Q_{r1}(k)$ is determined by the control law, we set the predictor of the dissolved oxygen concentration $S^{prd}_{O,nit}$ equal to the prescribed oxygen concentration level $S^*_{0,nit}$ and obtain, in terms of the control variable $Q_{air}(k)$:

$$Q_{air}(k) = \frac{\left(\hat{R}_2(k) + \frac{Q_{in}+Q_{r1}+Q_{r2}}{V_{nit}}S^m_{O,nit}(k)\right)}{a_0(C_S - S^m_{O,nit}(k))} - \frac{g_2(S^m_{O,nit}(k+1) - S^*_{O,nit}(k))}{T_s a_0(C_S - S^m_{O,nit}(k))} \tag{29}$$

With:

$$\begin{aligned} \hat{R}_2(k) &= (1 - \tfrac{4.57}{Y_A})\hat{\mu}_{A,nit}(k)\hat{X}_{A,nit}(k) \\ &+ (1 - \tfrac{1}{Y_H})\hat{\mu}_{Ha,nit}(k)\hat{X}_{H,nit}(k) \end{aligned}$$

The regulation is done under the following constrains:

$$Q_{air,min} < Q_{air}(k) < Q_{air,max} \tag{30}$$

The control action is then:

$$Q_{air}(k) = \begin{cases} Q_{air,min} & \text{if } Q_{air}(k) < Q_{air,min} \\ Q_{air,max} & \text{if } Q_{air}(k) > Q_{air,max} \\ Q_{air}(k) & \text{otherwise} \end{cases} \tag{31}$$

V. SIMULATION EXPERIMENTS

Simulation experiments were carried out by numerically integration of the complete model of the biological process. Numerical values of the parameters appearing in the model equations are given in table I and table II.

Variable	Value	Description
V_{nit}	1000 m^3	volume of nitrification basin
V_{denit}	250 m^3	volume of denitrification basin
V_{dec}	1250 m^3	volume of settler
Q_{in}	3000 m^3/j	influent flow rate
Q_{r1}	2955 m^3/j	recycled flow rate
Q_{r2}	1500 m^3/j	intern recycled flow rate
Q_w	45 m^3/j	waste flow rate
$X_{A,in}$	0 mg/l	autotrophs in the influent
$X_{H,in}$	30 mg/l	heterotroph in the influent
$S_{S,in}$	200 mg/l	substrate in the influent
$S_{NH,in}$	30 mg/l	ammonium in the influent
$S_{NO,in}$	2 mg/l	nitrate in the influent
$S_{O,in}$	0 mg/l	oxygen in the influent

TABLE I

PROCESS CHARACTERISTICS

Parameter	Value	Description
Y_A	0.24	yield of autotroph mass
Y_H	0.67	yield of heterotroph mass
i_{XB}	0.086	
K_S	20 mg/l	Affinity constant
$K_{NH,A}$	1 mg/l	affinity constant
$K_{NH,H}$	0.05 mg/l	affinity constant
K_{NO}	0.5 mg/l	affinity constant
$K_{O,A}$	0.4 mg/l	affinity constant
$K_{O,H}$	0.2 mg/l	affinity constant
$\mu_{A_{max}}$	0.8 1/j	maximum specific growth rate
$\mu_{H_{max}}$	0.6 1/j	maximum specific growth rate
b_A	0.2 1/j	decay coefficient of autotrophs
b_H	0.68 1/j	decay coefficient of heterotrophs
η_{NO}	0.8 1/j	correction factor for anoxic growth

TABLE II

KINETIC PARAMETERS AND STOECHIOMETRIC COEFFICIENT CHARACTERISTICS

The outputs variables are polluted with a 2% multiplicative signal noise and the design parameters of the control algorithms are the following: $Q_{r1,min} = 9000m^3/j$, $Q_{r1,max} = 20000m^3/j$, $Q_{air,min} = 0m^3/j$, $Q_{air,max} = 300m^3/j$, $g_1 = 0.75$, $g_2 = 0.85$, $T_s = 5min$, $y^* = 7.6mg/l$ and $S^*_{O,nit} = 3mg/l$

Simulation results are given in figures 1 to 6. The perturbations pursued on the control variables are due to measurement noises. The output variables evolution, that are the global nitrogen and the dissolved oxygen concentrations, and their corresponding reference trajectories are given in figures 3 and 4, respectively. The figures show the performance and the effectiveness of the regulator. In particular, one can appreciate the ability of the controller to track the desired values of the controlled

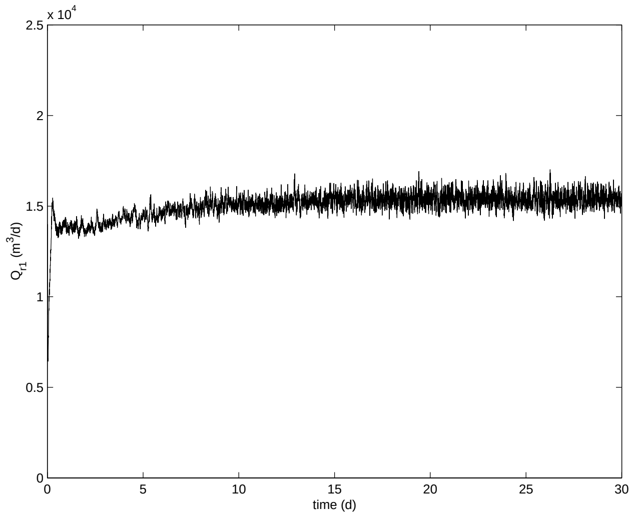

Fig. 1. Internal recycled flow rate

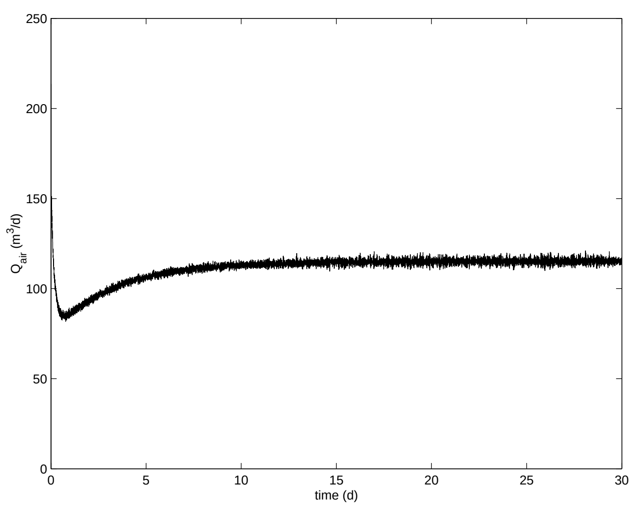

Fig. 2. Aeration flow rate

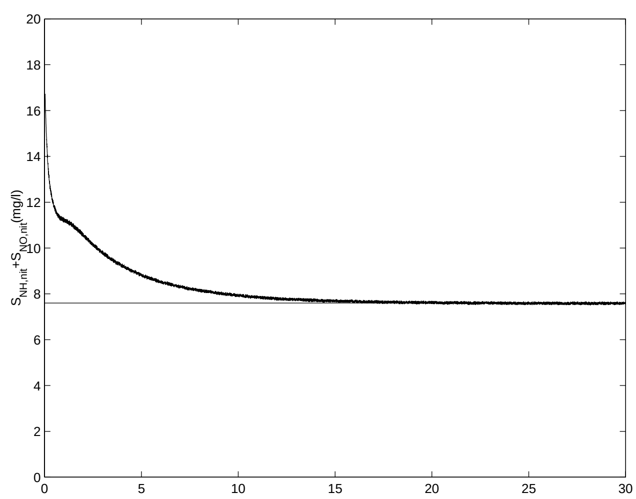

Fig. 3. Global nitrogen concentration

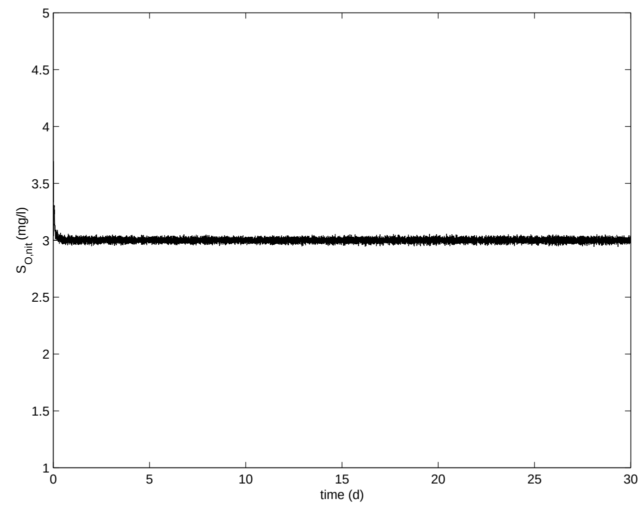

Fig. 4. Dissolved oxygen concentration

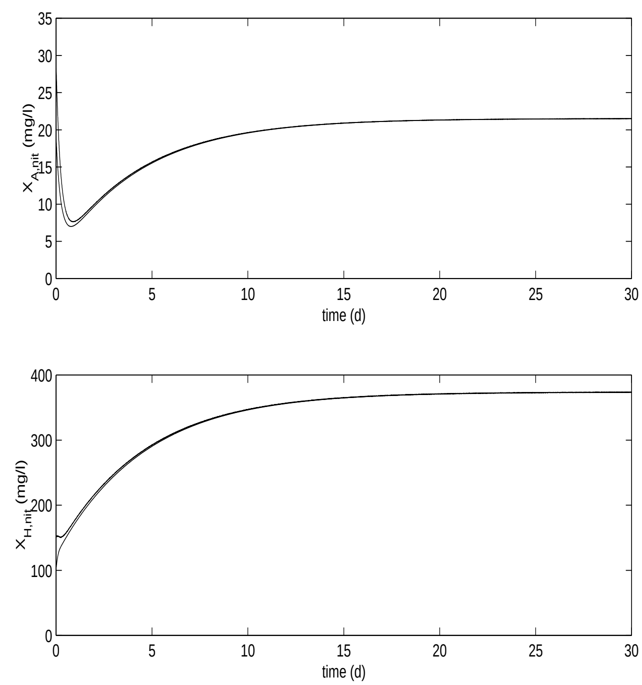

Fig. 5. Autotroph and heterotroph biomass concentration

variables. The evolution of the reconstructed autotrophic and heterotrophic biomass concentrations are depicted in figure 5. One can see that the estimation algorithm tracks suitably the biomass concentrations to their true simulated values with short transient responses. The estimator also provides good estimates of the specific growth rates, see figure 6.

VI. Conclusion

In this paper, an estimation and a predictive non linear controller for a biological nutrient removal have been proposed. The observer performs the twin task of states

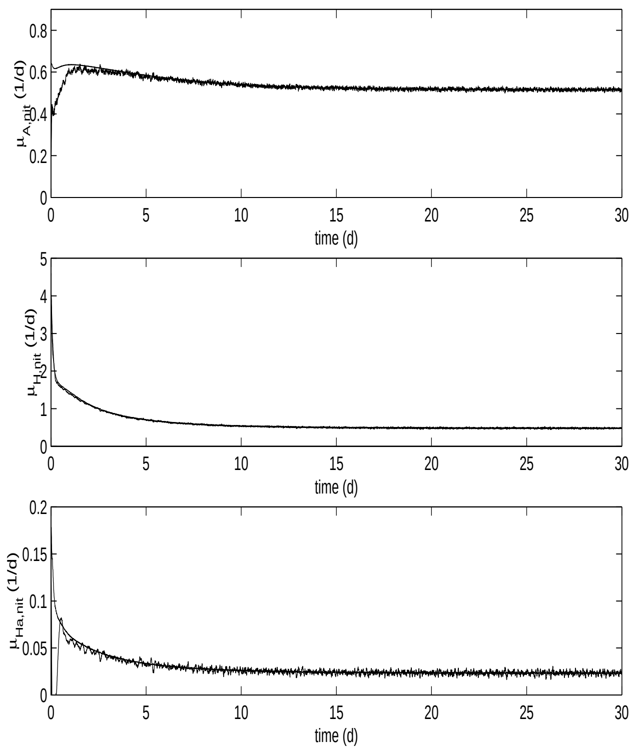

Fig. 6. Specific growth rates

reconstruction and parameters estimation. The control and estimation techniques developed are based on direct exploitation of the full non-linear IAWQ model. Simulation studies show either the efficiency of the non-linear controller in regulation or the effectiveness and the robustness of the estimation scheme, in reconstruction of the unmeasured variables and on-line estimation of the specific growth rates. The application of estimators such as 'intelligent sensors' to identify important biological variables and parameters with physical meaning constitutes an interesting alternative to the lack of sophisticated instrumentation and provides real time information on the process.

Acknowledgment

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