Postdoc Fellowships for non-EU researchers

Final Report

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Selection	2012
Host institution	Service d'Automatique, UMONS
Director	Alain Vande Wouwer
Period covered by this report	from 15/02/2013 to 14/08/2013 and 01/08/2014 to 15/11/2014
Title	**Optimizing control of biotechnological processes by output feedback**

1. Objectives of the Fellowship (1/2 page)

Bioprocesses are becoming increasingly important in several sectors, including the production of pharmaceuticals, the development of agro-food products, the treatment of organic wastes and wastewater, and in the production of renewable energy by the direct conversion of biomass, either biogas, biodiesel or bioethanol.

In order to increase the productivity, quality, robustness, and efficiency of the latter processes, as well as to decrease production costs, it is required to monitor parameters or variables, optimize operating conditions and supervise continually their behavior. However, the implementation of suitable monitoring and automatic control schemes is not always easy in biotechnological processes, due to the large uncertainty in the mathematical models of the underlying bioprocesses and the lack of sensors that would allow on-line reliable measurements of key metabolites.

The proposed research project finds its roots in the current research topics developed at the Service d'Automatique and BioSys center of the Université de Mons (UMons) and the Instituto de Ingeniería of the Universidad Nacional Autónoma de México (II-UNAM). In particular, at II-UNAM, research is dedicated to robust observer design schemes applicable to bioprocesses and the implementation of process control to experimental laboratory–scale biosystems. The group at the Laboratory for Research on Advanced Processes for Water Treatment (LIPATA) of II-UNAM is also concerned with the application of output feedback controllers for enhancing production of hydrogen in dark anaerobic digesters or in bio-electrochemical systems. On the other hand, the group at UMons has expertise in dynamic real-time optimization, in particular extremum-seeking optimizing control strategies, as well as observer design. The BioSys center has experimental facilities for the cultivation of microalgae in photo-bioreactors, and the cultivation of bacteria and animal cells at different laboratory scales.

The project aims at summing up the capabilities of both research groups to tackle the problem of designing suitable output feedback optimizing control schemes for biotechnological processes.

Two technologies that are promising for energy production are the production of hydrogen from organic residues, either in dark anaerobic bioreactors or in bio-electrochemical systems, and the production of lipidic oils suitable to produce biodiesel from the cultivation of marine microalgae in photo-bioreactors.

Both processes are challenging from the viewpoint of process control, since their mathematical models are uncertain both in parameters and structure, and are highly nonlinear. Furthermore, the information that can be extracted from these systems as on-line measurements is limited. These processes also have operating points that are optimal in terms of productivity rates, conversion efficiency or some other economically interesting criterion, but these operating points may not be known a priori, so they must be found and/or adapted while the process is running.

Therefore, the general objective of the project is to propose automatic control schemes that optimize in real-time the operating point of the two above mentioned processes according to some criteria, based on limited information from measurement sensors, despite uncertainties in the model parameters and/or structure.

The proposed approach to tackle this challenging objective is to follow 3 complementary research streams:

1. Real-time optimal (RTO) control, and in particular extremum seeking strategies, for the on-line search of the optimal operating conditions. The group at UMons has proposed extremum seeking strategies for cultures of micro-organisms exhibiting overflow metabolism (Dewasme et al., 2011), whereas the group at II-UNAM has proposed an alternative for certain wastewater treatment systems (Vargas et al., 2011).
2. Robust observer design, and in particular sliding mode and interval observers, for the estimation of unmeasured key components. Sliding mode observers are promising approaches, which are subjects of investigation at II-UNAM (Moreno, 2011; Moreno et al., 2010; Moreno, 2009), whereas interval observers have been investigated at UMONS (Goffaux et al., 2009).
3. Tailored output feedback controllers for fast tracking of optimal setpoints. In particular, experience has shown that this is possible for several practical examples (Donoso-Bravo et al., 2011; Mailier et al., 2011; Moreno et al., 2006; Pat et al., 2011; Montaño and Vargas, 2010; Vargas et al., 2009).

2. Methodology in a nutshell (1/2 page)

During the research stay at UMons, work has been centered on the design of on-line optimizing output feedback control for the production of hydrogen from organic residues, either in dark anaerobic bioreactors or in bio-electrochemical systems, and the production of valuable products from the cultivation of marine microalgae in photo-bioreactors. Based on available mathematical models and available experimental data of the processes, the proposed control schemes have been tested using numerical simulators. This includes the design of the extremum-seeking controllers, the testing and implementation of robust observers and the evaluation of the tailored solutions for the biotechnological processes under consideration.

The following activities were planned:

1. Study the mathematical models available for the cultivation of microalgae in photo-bioreactors which already operate at UMons;
2. Review of recent RTO schemes, including new ones proposed by the group at UMons;
3. Review of robust observer design schemes, especially those proposed by II-UNAM and UMons;
4. Proposal of tailored feedback control schemes for the biotechnological processes studied at II-UNAM and UMons;
5. Design of observers for the considered biotechnological processes;
6. Development of numerical simulators of the processes in order to test the proposed observer and control schemes;
7. Supervision of experimental testing of the microalgae cultivation bioreactors at UMons, both to gather data for the simulations, as well as for application of the designed controllers and observers;

8. Writing and submitting for publication the (partial) results of the research in conference proceedings and scientific journals; colleagues from II-UNAM and UMons will be coauthors in these publications and it is expected to publish results in at least one scientific journal.

3. Results (6-8 pages)

a) Results relative to bacteria cultivation (overflow metabolism)

During the stay we started working on the problem of output-feedback extremum-seeking control for biotechnological processes, considering as application example the cultivation of bacteria in bioreactors. This is an ongoing investigation at UMONS and research has concentrated on the mathematical modeling of the process using data from an experimental pilot bioreactor. Although the feedback control scheme had already been proposed and tested on a simulation platform, we were still lacking the possibility of measuring a critical variable. This variable is an indicator of the activity of the bacteria and achieves a maximum whenever the process is most efficient. The variable cannot be measured directly, but there are other on-line measureable variables that can be used to estimate its value, namely the biomass concentration and the oxygen and carbon dioxide transfer rates. For this reason, we dedicated the first part of the stay to the development of an estimator or *software sensor* for this variable. We used the theory of second order sliding modes to design a so-called super-twisting observer to propose an estimator that is robust against some inevitable perturbations and parameter uncertainty. This is an important outcome of the stay and resulted in a presentation and abstract presented at a regional conference and the publication of an article and an oral presentation at a conference in India. Finally, it also resulted in a publication in the *Journal of Process Control*, whose abstract and main results appear below.

- Vargas, A. Vande Wouwer, J.A. Moreno (2014). A weighted variable gain super-twisting observer for the estimation of kinetic rates in biological systems, *Journal of Process Control* 24(6): 957-965, doi: 10.1016/j.jprocont.2014.04.018, ISSN 0959-1524.

Abstract: The knowledge of kinetic reaction rates is important for monitoring and controlling biotechnological processes. However, the lack of on-line sensors for this purpose and the inherent problems with numerical differentiation make observers indispensable. In this work, we propose the use of a weighted variable gain super-twisting observer (WVGSTO), applicable to a class of second-order nonlinear systems that include a measurable weight on the unmeasured variable and the possibility of bounding the perturbations with measurable functions. This estimation method is illustrated with an academic example and then applied to a fed-batch bioprocess.

Main results: In this paper we provide a generalized super-twisting observer (WVGSTO) which is able to estimate an unmeasured state exactly and in finite time, when this state is multiplied by a known time varying signal which does not change sign. Using the WVGSTO it is possible not only to generalize and to extend, but also to unify, many results in the literature for the estimation of the reaction rates in bioprocesses, including the super-twisting observer (STO) and the high-gain observer (HGO) that have been proposed by other authors. We show that in this case a quadratic Lyapunov function with constant matrix P allows us to assure the convergence of the observer in finite time and despite the perturbations using time-varying gains. We provide in the paper a study example to illustrate the application of the WVGSTO for the estimation of reaction rates and states in a particular bioprocess. The system considered has the following structure:

$$\begin{aligned}\dot{x}_1 &= f_1(x_1,u) + b(t,u,y)x_2 + \delta_1(t,\boldsymbol{x},u)\\ \dot{x}_2 &= f_2(x_1,x_2,u) + \delta_2(t,\boldsymbol{x},u,w)\\ y &= x_1\end{aligned} \tag{1}$$

Since many existing observer algorithms can be used for this purpose, we will list the distinguishing properties of the proposed observer, given the

1. It is able to estimate exactly the second state after a finite time and robustly with respect to uncertainties/perturbations, represented by $\delta_2(t,\boldsymbol{x},u,w)$ in (1), that are persistent. In order to achieve this feature it is necessary to introduce discontinuous functions in the injection terms of the observer. It is important to note that finite time convergence can also be achieved with continuous injection terms (though not locally Lipschitz in the neighborhood of the origin), but only in the absence of uncertainties/perturbations.
2. The proposed observer is able to converge in a finite time that is independent of the initial condition of the plant and of the observer. In order to achieve this property it is required to introduce not globally Lipschitz injection terms.
3. The observer is able to deal with a known function f_1 that is continuous but not necessarily Lipschitz (globally or locally). The function f_2 can be discontinuous, it does not have to be locally or globally Lipschitz in $x_1$and it can grow linearly in x_2.
4. When a bounded uncertainty/perturbation δ_1 is present, the estimation error will be bounded. The same will be true in the presence of measurement noise.
5. All proofs are based on Lyapunov's method. The Lyapunov functions used here are of quadratic type, so that the mathematical machinery required is very similar to what is needed for linear systems.
6. The proposed method can be considered as a generalization and improvement of other observer design methods in the literature. In particular, it includes a linear observer with variable-gains and the high-gain observer.

The main theorem provides conditions for the design of a super-twisting observer with time-varying gains, given the knowledge of two continuous functions that act as bounds for the perturbations and differences between the true variables x_1, x_2 and their estimated values $\hat{x}_1, \hat{x}_2$. The perturbations δ_1 and δ_2, and the difference between the evaluation of f_1 and f_2 with estimated and true variables, defines unknown functions ρ_1 and ρ_2 in the dynamics of the error system. The second one does not have to vanish at the origin, while the first one does. The procedure for the design is explained in the paper and leads to a discontinuous observer that converges in finite time and is robust to perturbations in the unmeasured variable. An academic example is used to illustrate the advantages of the new observer, comparing it to fixed gain counterparts.

Afterwards, as application example we considered the model of a fed-batch bioreactor where substrate is consumed to grow biomass at a time-varying rate proportional to the biomass concentration. Although we know in the model that the growth rate follows Monod kinetics, we assume that its defining parameters have large uncertainties around a nominal value. The objective then is to estimate this growth rate using on-line measurements of both the substrate and the biomass concentrations, despite these large uncertainties. The solution proposed is to cast the problem as a second order system with the substrate as measured variable and the growth rate as unmeasured variable, considering an alternative representation for its dynamics (i.e. the right hand side of the differential equations), which has a known structure, but time-varying parameters which are constrained to a certain bound that is indeed known but evolves with time. This is exactly the form needed for the proposed WVGSTO. The simulation results show good convergence properties, even with some measurement noise added. In fact, a classical Kalman filter or a high-gain observer would not be able to achieve the convergence without error that is observed with the proposed WVGSTO.

In conclusion, we used a generalization and extension of the classical super-twisting observer (STO), that we call weighted variable gain super-twisting observer (WVGSTO) in several directions: (i) it allows known time-varying coefficients of the unmeasured states; (ii) it includes continuous and discontinuous injection terms, so that the performance of the observer can be improved; (iii) it allows time-varying observer gains and time-varying perturbation bounds; (iv) it includes as special cases many previous observation schemes, as the HGO or the STO; and (v) the convergence and performance proofs are all unified and are simple, since they use the linear-like framework originally presented in previous works by some co-authors.

b) Results relative to microalgae photobioreactors

In order to propose the new software sensor, we had to study further the theory of second-order sliding modes. This lead to the development of a new super-twisting observer that takes into account the changing influence of the biomass concentration and has variable gains. This new development has found an application in the estimation of the nitrogen quota in a marine microalgae bioreactor, where the total biomass and the nitrogen substrate are measured on-line. An article was first submitted to *10th IFAC International Symposium on Computer Applications on Biotechnology (CAB-2011)*, which took place in Mumbai, India, 18-20 December, 2013. It was presented orally as a semi-plenary and we later received an invitation to submit an extended version of the work to the *Journal of Process Control*; this was done in May, 2014 and we are still waiting for the review process to finish, hoping for acceptance and eventual publication. In it, we use the so-called weighted variable gain super-twisting observer (WVGSTO) to estimate the biomass growth and the substrate consumption rates, and an asymptotic observer to estimate the quota. The new feature of the submitted article is the simulation of the observer in closed loop using a two-level controller that uses the estimated reaction rate to decide between two values of the dilution rate. This was ongoing research that continued after returning to Mexico in 2013, and was later worked on during the second part of the BELSPO grant in late 2014.

Another result regarding microalgae cultures was a recently accepted paper that dealt with the development of a sensor for on-line measuring the biomass concentration in a photobioreactor (PBR).

The main results of both papers are presented below (abstract and main results):

- A. Vargas, A. Vande Wouwer, J.A. Moreno (2014). A weighted variable gain super-twisting observer for the estimation of kinetic rates in biological systems, *Journal of Process Control* 24(6): 957-965, doi: 10.1016/j.jprocont.2014.04.018, ISSN 0959-1524.

Abstract: In biotechnological processes such as fed-batch reactors the lack of reliable and robust on-line sensors and the limited number of actuators makes the task of operating at optimal conditions very difficult. In this contribution we present a feedback controller that aims at regulating the substrate concentration at an optimum value such that biomass production is enhanced while by-product formation is not. We use a virtual output that is estimated using a bank of weighted super-twisting observers to drive an output-feedback extremum-seeking controller. The only measurements needed are the biomass concentration and the oxygen and carbon dioxide mass transfer rates. Simulation results on a fed-batch bioreactor model show the applicability of the proposal.

Main results: It is common in biotechnological applications to optimize the operation of fed-batch bioreactors to attain a desired performance by manipulating the feed rate. A particular case is the maximization of the final biomass while minimizing an undesired by-product.

The fed-batch growth of certain strains of *E. coli* presents overflow metabolism: its catabolism has a limited energy production for cell growth and di- vision because of a limited capacity to oxidize the main substrate, usually glucose. Thus, under excess of this nutrient, it can follow another metabolic pathway more commonly known as fermentation, producing a by-product which is generally a growth inhibitor, e.g. acetate.

The mathematical description of this process involves three reactions: substrate oxidation, substrate fermentation, and by-product formation. The last two reactions occur only after the substrate is in excess, i.e. until its concentration is above the critical value, while the first one has a limited rate after this critical value. The state variables are the biomass (X), the substrate (S), the by-product (P), the dissolved oxygen (O) and the CO2 (C) concentrations, as well as the current volume in the reactor (V). It has a main control input which is the dilution rate $u = Q_{in}/V$, where Q_{in} is the volumetric inflow rate. Other inputs to the system are the substrate inflow concentration (S_{in}) and the supplied oxygen through agitation or a sparger, influencing the mass transfer coefficient ($k_L a$).

We consider in this contribution a simplified model of the system, where the third reaction is assumed negligible and thus no by-product (acetate) is formed. Then we can write the system as

$$\dot{\boldsymbol{\xi}} = \boldsymbol{K\rho\xi} - \boldsymbol{\xi u} + \boldsymbol{f}, \qquad \boldsymbol{\xi}(0) = \boldsymbol{\xi_0}\,, \tag{2}$$

where $\boldsymbol{\xi} = [X \quad O \quad C \quad S]$ is the state vector, $\boldsymbol{K}$ contains the pseudo- stoichiometric coefficients, u is the dilution rate, and $\boldsymbol{f}$ is the vector of gas and mass flow rates in and out of the reactor, containing the oxygen and CO_2 transfer rates. The specific reaction rate vector is $\boldsymbol{\rho} = [r_1 \quad r_2\,]$, where r_1 is the respiration rate and r_2 is the fermentation rate, which depend on a critical rate r_S^*:

$$r_1 = \min(r_S, r_S^*), \qquad\qquad r_2 = \max(0, r_S - r_S^*)\ . \tag{2}$$

Substrate (glucose) is consumed with rate r_S, which follows a Monod model and the critical rate r_S^* defines a critical substrate concentration S^* such that respirative regime occurs when $S(t) < S^*$ and respiro-fermentative regime occurs when $S(t) > S^*$. Although it is not modeled here, acetate is produced in respiro-fermentative regime, but only slowly consumed in respirative regime. This by-product (P) is inhibitory for biomass growth, as its accumulation decreases the critical consumption rate r_S^*.

The best strategy for enhancing biomass production without accumulating acetate is thus to operate in the boundary between regimes, i.e. maintaining $S(t)$ at the critical value S^*. This way, no acetate is produced and thus the critical r_S^* remains at a maximum, leading to maximum biomass growth. However, S^* is not known a priori and furthermore it may decrease slowly during the fed-batch cultivation if acetate accumulates.

For this reason real-time optimization (RTO) schemes have been proposed. They use a virtual output that is a linear combination of the two main reaction rates in the process: $y = r_1 - r_2$. This output reaches a maximum whenever $S(t) = S^*$ and thus $y = r_S^*$. The controllers proposed manipulate the dilution rate $u(t)$ to keep $y(t)$ near its optimum value at r_S^* . Previously the group at UMONS had proposed the use of an extremum-seeking strategy that provides an estimate of S^* to regulate $S(t)$ at this value; it assumes on-line measurement of $S(t)$. In contrast, the group at UNAM had proposed the use of a modified PI-controller to regulate $y(t)$ at its maximum value y^* without the need to measure S.

A problem with these controller proposals is that this output cannot be measured directly. This is why we call it a virtual output. The group at UMONS had proposed an algebraic approach to estimate it under the assumption of quasi-steady-state, perfect knowledge of the matrix $\boldsymbol{K}$, and measurement or knowledge of all the signals in $\boldsymbol{f}(t)$. However, it has the disadvantage of being very sensitive to the exactness of the matrix $\boldsymbol{K}$ of pseudo-stoichiometic coefficients and it only estimates the quantity $(r_1 - r_2)X$, so it also becomes sensitive to the noise present in X.

In the CAB2013 paper we proposed the use of a bank of super-twisting observers to estimate the virtual output. The approach uses only the on-line measurements of X, O, and C (using probes), as well as $\boldsymbol{f}(t)$. (using a gas analyzer). Measurement of S is not needed, nor the knowledge of S_{in}. Knowledge of the matrix $\boldsymbol{K}$ is assumed, but if this is not possible, a methodology is proposed to build an estimate of its underlying structure, given gathered data from a previous batch operation.

In this contribution we explained further the estimation procedure for the virtual output using the bank of observers and combine the use of the observer with a simple discrete two-level extremum-seeking controller. This leads to an output-feedback controller that is able to bring substrate trajectories close to the optimum value $S^*(t)$ and thus enhance the biomass growth.

An output-feedback extremum-seeking controller has been proposed for optimizing the biomass production in a fed-batch bioreactor with overflow metabolism. A virtual output that is computed using a bank of super- twisting observers was used; this output is computed as the average of several redundant estimations. The observer is sensitive to the choice of pseudo- stoichiometric matrix coefficients, and therefore an additional procedure to estimate its structure has been proposed. As expected, it is also very sensitive to noise in the measurements, but the redundancy of the bank of observers can help. Simulations on a realistic mathematical model show very good results. It must be pointed out, however, that a bad initial choice of this matrix can lead to poor results (which was not shown in the simulations). However, a practical solution could be to operate the system manually for the first batch, alternating between two input values periodically, and with the data gathered use the optimization procedure to find the structure of the matrix $\boldsymbol{K}$. The two levels used in the controller could also be refined by inspection of past batches. This could be the topic of further investigations.

- M. Benavides, J. Mailier, A.-L. Hantson, G. Muñoz, A. Vargas, J. Van Impe, A. Vande Wouwer (2014). Design and test of a low-cost RGB sensor for online measurement of microalgae concentration within a photo-bioreactor, *Sensors*, (in print), ISSN 1424-8220.

Abstract: In this study, a low-cost RGB sensor is developed to measure online the microalgae concentration within a photo-bioreactor. Two commercially available devices, *i.e.*, a spectrophotometer for offline measurements and an immersed probe for online measurements, are used for calibration and comparison purposes. Furthermore, the potential of such a sensor for estimating other variables is illustrated with the design of an extended Luenberger observer.

Main results: Research and applications of microalgae cultivation have experienced a remarkable increase in the last two decades due to a renewed interest in alternative energy sources, and the potential of microalgae to produce large quantities of neutral lipids (e.g., 20%–50% dry cell weight) for biodiesel production. Besides, microalgae have a large spectrum of applications ranging from the production of pigments, cosmetics and animal fodder to wastewater treatment. These ever increasing applications motivate the development of process monitoring and control, in order to improve process reliability and productivity. However, process instrumentation remains problematic, and it is usually not possible to measure online all the component concentrations of interest. An appealing alternative is therefore the development of a process model, and the design of an observer, or software sensor, blending the predictive capability of this dynamic model and the information from the available online sensors.

A classical model of microalgae cultivation under substrate limitation is the one originally proposed by Droop and it has been demonstrated that observability is achieved when biomass is measured. In other words, other state variables, such as the extracellular concentration of substrate and the internal substrate quota, can be reconstructed online based on the process model and the available biomass measurement, provided that this measurement does not vanish (this is a requirement for having not only online information but also a properly operating photo-bioreactor). The biomass concentration therefore appears as a key measurement in order to set up a monitoring and control system.

Nowadays, conventional methods for measuring biomass include sample dry weight, direct count using microscopy, spectrophotometry, protein concentration, or fluorescence. However, some of these methods can be time-consuming, destructive when they are based on sampling, and relatively costly in terms of acquisition costs or maintenance. Some recent developments include also a photo-electrochemical sensor and the measurement of O_2 generation.

In this context, there is a clear incentive for the development of low-cost sensors that would be appropriate for biomass online monitoring, and in this work, we propose as a biomass online measurement method the use of a low-cost RGB light sensor to estimate the turbidity of the medium containing the microalgae. In this section, we describe the turbidity acquisition method, the luminance, turbidity and biomass relationships, and the materials used to implement the biomass sensor.

RGB sensors have already been used in related applications, such as the measurement of wine or oil color by means of optical fiber, showing satisfactory results with a low cost implementation. The data measured by this sensor is correlated to the biomass concentration in an external personal computer. The behavior of our proposed sensor is compared with that of a commercial optic online sensor, both working simultaneously in the same batch culture implemented in a photo-bioreactor for *Dunaliella tertiolecta*.

In order to characterize our proposed sensor, the biomass concentration of the microalgae culture obtained by a commercial UV spectrophotometer was used as a reference. Then, the calibration procedure, sensitivity, accuracy and precision were obtained and presented. We compared our proposal with a commercial online sensor working in parallel in a microalgae culture implemented in a PBR. The results showed that our proposal might be a suitable solution for online biomass concentration measurement. Finally, an example of its potential application in monitoring and control process was detailed. Future works will consider the use of our proposal in a controlled plant for microalgae cultures.

c) Results relative to membrane bioreactors

Another research activity concerned the contribution to the development of a mathematical model to explain the fouling in a real membrane bioreactor (MBR). This is being done as part of the thesis of Guilherme Araujo-Pimentel, a Ph.D. student at UMONS, in collaboration with the Laboratory of Chemical and Environmental Engineering (LEQUIA), *Universitat de Girona*, Spain. The contribution of II-UNAM was mainly in the development of the model, while LEQUIA provided real-time data from an MBR of a small wastewater treatment plant. The outcome will be presented at the 2015 Vienna Conference on Mathematical Modelling (Mathmod), to be held in Vienna, Austria, 18-20 February, 2015.

- G. Araujo Pimentel, M. Dalmau, A. Vargas, J. Comas, I. Rodriguez-Roda, A. Rapaport, A. Vande Wouwer (2015). Validation of a simple fouling model for a submerged membrane bioreactor, *Vienna Conference on Mathematical Modelling (Mathmod)*, Austria, 18-20 February, 2015 (presented by G. Araujo Pimentel).

Abstract: Most of the published membrane bioreactor (MBR) models have been proposed for process description and gain of insight, resulting in a large number of parameters to estimate from experimental data. These models are usually too complex for process control, and there is a need for simple, dedicated, dynamic models. In this study, attention is focused on the fouling phenomenon, which hampers the efficient operation of MBRs, and a simple model is proposed and validated using a large database collected from a pilot plant. This model includes several manipulated variables, e.g., the effluent flow rate and the air crossflow, as well as a measurable perturbation such as the ambient temperature. To ease the identification procedure, a separation of the time scales of the process in slow and fast dynamics is exploited. The results show that the model can be used to predict the trans-membrane pressure behavior in a medium-term, about 10 days ahead.

Main results: The aerobic submerged membrane bioreactor (sMBR) has been increasingly applied to wastewater treatment, due to its high effluent quality (regarding solid matters), footprint reduction and the decoupling of the hydraulic and solid retention times. In its simple configuration, an sMBR combines the function of an activated sludge system with secondary and tertiary filtration in a single tank. One of the main drawbacks of the sMBR process is the fouling phenomenon, caused by particles that attach to the membrane surface decreasing process efficiency and increasing energy consumption.

The dynamic behavior of such systems has been modeled with different degrees of detail. The existing models range from the description of the physical interaction of constituents inside the cake on the membrane surface, to black-box mathematical models that mimic the fouling build-up.

Most of these models are not appropriate for process control, as they are either too complex and contain parameters that are difficult to estimate from experimental data, or they lack physical interpretation. Simple dynamic models, in particular of the fouling mechanism, would however be very useful to optimize plant operation and develop controllers.

In previous studies by the group at UMONS a simple model combining biological and physical phenomena has been proposed and analyzed in terms of dynamics, time-scale separation, and equilibrium points. In the present contribution, attention is focused on the fouling mechanism only, and an even simpler dynamic model is proposed, calibrated and validated with experimental data collected from a pilot plant. With respect to the previous contributions, a new influence variable is also taken into account, namely the ambient temperature variation. To estimate the model parameters, a time-scale separation approach is used, which allows subsets of parameters to be estimated independently.

The proposed model for an sMBR process was validated with a large quantity of experimental data, in short and long terms. The transmembrane pressure (TMP) dynamics can be reproduced by the model with good accuracy, validating the model horizon prediction property. The time-scale separation based on the fast and slow study simplified and decreased the computational effort on the parameter identification procedure, resulting in the possibility for on- line prediction of TMP. As future work, the capacity of the model to predict TMP evolution in real-time TMP model-based process control will be studied.

4. Perspectives for future collaboration between units (1 page)

During the stay we prepared and submitted two important project proposals, which would allow further collaboration in a stimulating context

1. *Nonlinear state estimation: robust and stochastic approaches – Applications to biological systems*, submitted to the call for bilateral collaboration projects funded by FNRS (Belgium) and CONACYT (Mexico). Its main objective is the development of dynamic models that are suitable for control of bioprocesses within biorefineries, and of a practical methodology to design experiments and achieve the parametric identification of these models; the emphasis will be on practical results and pragmatic approaches.
2. *ELAC2014/BEE-0179. Biorefinery of organic waste based on a three stage anaerobic fermentation. Design, operation, and numerical investigation (BODONI)*. This proposal is within the ERANet-LAC first Joint Call on Research and Innovation, funded by the European Commission, by the 7th Framework Programme for Research and Technology Development (FP7). It involves 8 partners from 7 countries (Belgium, Chile, Germany, Mexico, Norway, Peru and Spain). The main objective of the project is to perform key biotechnological and process research for the development of a new, scalable high productivity biotechnological production process of hydrogen, methane, ethanol, butanol and volatile fatty acids from waste streams, both homogeneous and heterogeneous. We participate in several work packages with modeling and control proposals.

As part of the collaborative work we have involved several students, both at UNAM and at UMONS. Below is a list of the students and a brief explanation of their involvement within the project. The respective participation in the supervision of these students is also an important factor of our collaboration.

1. Julián Oviedo Santana. “Modelling and estimation for bio-energy producing processes”, Doctorate Studies, Université de Mons.
   The work is concerned with the development of models and the application of parameter estimation techniques for both a microalgae photobioreactor at UMONS and a PHA producing process in Mexico.
2. Gerardo Muñoz Montoya. “Optimization of biorefinery process for PHA production using automatic control”, Doctorate Studies, UNAM.
   He did a research stay at UMONS as he was a master student. Now he is working on process control schemes for PHA production processes in Mexico.
3. Micalea Lucía Benavides Castro, “Contribution to Modeling and Estimation of Microalgal Cultures in a PBR”, Doctorate studies, Université de Mons.
   We have collaborated on the development of the super-twisting observer for her microalgae system.
4. Cristina Retamal, “Monitoring and modelling of *E. coli* BL21(DE3)”, Doctorate studies, Université de Mons.
   We have developed a virtual output estimator based on the super-twisting observer and continue with the development of extremum-seeking process control schemes for the system.
5. Guilherme Araujo Pimentel, “Monitoring and modelling of *E. coli* BL21(DE3)”, Doctorate studies, Université de Mons.
   We have collaborated in the proposal of a model for the fouling behavior of a membrane bioreactor.

5. Valorisation/Diffusion (including Publications, Conferences, Seminars, Missions abroad...

1. L. Dewasme, A. Vargas, J.A. Moreno, A. Vande Wouwer (2012). Real-time optimization of a fed-batch bioreactor with substrate inhibition using extremum-seeking, *2012 IEEE Multi-conference on Systems and Control*, Dubrovnik, Croatia, 3-5 October, 2012 (presented by L. Dewasme).
2. A. Vargas, A. Vande Wouwer (2013) Bioreactor virtual output estimation using super-twisting observers, *32nd Benelux Meeting on Systems and Control,* Houffalize, Belgium, 26-28 March, 2013 (presented by A. Vargas).
3. A. Vargas, A. Vande Wouwer, J.A. Moreno (2013). Virtual output estimation in a bioreactor using a generalized super-twisting algorithm, *10th IFAC International Symposium on Computer Applications on Biotechnology (CAB-2007)*, Mumbai, India, 18-20 December, 2013 (presented by A. Vande Wouwer).
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7. G. Araujo Pimentel, M. Dalmau, A. Vargas, J. Comas, I. Rodriguez-Roda, A. Rapaport, A. Vande Wouwer (2015). Validation of a simple fouling model for a submerged membrane bioreactor, *Vienna Conference on Mathematical Modelling (Mathmod)*, Austria, 18-20 February, 2015 (presented by G. Araujo Pimentel).

6. Skills/Added value transferred to home institution abroad (1/2 page)

During the stay A. Vargas had the opportunity to attend two short courses that enriched his knowledge about control systems, and could later find applications in my current research lines. These were:

1. "Robust Control: An LMI Based Perspective", Université de Mons, Belgium, 24 and 26 October, 2012 (http://www.umons-biosys.org), dictated by Prof. Daniel Coutinho, Federal University of Santa Catarina, Brazil.
2. "Model Predictive Control: Basic Concepts and Formulations", Université de Mons, Belgium, 3 - 4 October, 2012 (http://www.umons-biosys.org), dictated by Prof. Lino Santos, University of Coimbra, Portugal.

Besides these two courses, the stay of A. Vargas had a very positive impact on his activities upon returning to Mexico. He gained knowledge on the system identification techniques that have been proposed by UMONS, which he is now applying for some bioreactor systems in his laboratory. Especially, the stay benefited in the co-supervision of a P.D. thesis of one of his former students, who is now at UMONS, and who will partially work on a model of a PHA production bioreactor in Mexico. We are also now considering signing an official student exchange agreement between UNAM and UMONS. The submission of the two project proposals explained above, which will benefit both parties and strengthen their collaboration, is also an added value of the stay.

Another benefit of the ongoing collaboration was the invitation of Prof. Vande Wouwer to teach a 12-hour short course in Querétaro: "An introduction to nonlinear model identification – application to bioprocesses", 9-11 July 2014. It was financed by a current bilateral agreement CONACYT/FNRS project and by the Mexican Association for Automatic Control (AMCA); more than 25 graduate and bachelor students from Querétaro and neighboring states attended.